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CONTRACT REPORT NO. 3-167

GROUND-CRAWLING: 1966
THE STATE-OF-THE-ART OF DESIGNING
OFF-ROAD VEHICLES

by

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by

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PREFACE

This survey of the state-of-the-art of the design of ground-crawling, off-road vehicles was conducted by Wilson, Nuttall, Raimond Engineers, Inc. (WNRE), under contract DA 21-079-eng-392 with the U. S. Army Engineer Waterways Experiment Station (WES). It comprises a portion of the mobility environmental research study (MERS), sponsored by the Office, Secretary of Defense, Advanced Research Projects Agency (ARPA), Directorate of Remote Area Conflict, for which WES is the prime contractor, and the U. S. Army Materiel Command (AMC) is the service agent. The funds employed for this study were allocated to WES through AMC, under ARPA Order No. 400. The overall object of the MERS project was to focus the results of the ground mobility and vehicle-terrain research of the preceding 20 years upon the problems of rationally designing and/or selecting proper off-road vehicles for military use in remote areas, particularly in the tropics and subtropics.

Project MERS was severely truncated after one year of a planned three-year effort, leading indirectly to an unconscionable delay in the completion of this report. Although the principal findings of this study were communicated earlier (WNRE, 1964, 1965),^{*} the present synthesis was not, nor could it have been.

The period of delay has seen the escalation of the U. S. role in Southeast Asia from providing advice to the conduct of extensive land warfare by U. S. troops. The experience of actual war,

^{*}References are tabulated beginning on p. 291.

however remote, has influenced the present synthesis, as no doubt it has the concepts of others interested in off-road vehicle problems. The dramatic practical demonstration of air-mobile operations on the one hand and of the patent inadequacy of our current family of ground-bound vehicles on the other, has drastically altered the climate within which ground-crawling vehicle problems must be tackled. The author makes no apology for his accidental good fortune in having been spared making his addition to the considerable inaccurate speculation already published on these crucial points, and on many others.

The conduct of this study, which in fact continued until the present, involved the review of many hundreds of published reports covering the spectrum of terrain, vehicle, and operations features, and discussions and correspondence with several hundred knowledgeable people around the world. The author's appreciation for their various contributions and influences can here only be acknowledged in general terms. However, the entirely tangible support and assistance of MERS/WES project personnel, A. A. Rula, R. D. Wisner, and R. R. Priest, can be and are specifically and gratefully noted.

SUBJECT

The object of this study is to outline and to evaluate the current state-of-the-art of off-road vehicle design, with particular reference to military vehicles and to their performance off-road. A state-of-the-art study generally implies some dissatisfaction with the existing situation, and that is the present case. Accordingly, a further object of the study is to review the general procedures by which military vehicles for off-road use are conceived and eventually reach the field, and to suggest means, technical and/or organizational, to improve matters.

SUMMARY

The state-of-the-art of off-road vehicle design, in particular relation to the off-road performance of military vehicles, is basically sound, although the approach to off-road performance has thus far been largely pragmatic. In recent years there has been steady improvement in the overall mobility and/or reliability of all classes of military off-road vehicles.

Recent improvement in the soft ground mobility of tactical trucks has been substantial. The performance of tactical trucks now equals or exceeds that of similar foreign military vehicles and of commercial wheeled vehicles, excepting only such extreme special purpose machines as marsh buggies. Some possibilities to raise soft-ground mobility to still another significantly higher level in practical, working vehicles are evident and, in part, already under study.

The reliability and overall off-road performance of tracked vehicles have also progressed significantly, but the basic soft-ground mobility of various classes has, apparently by choice, remained static. A number of working, commercial tracked vehicles, some articulated on various patterns, have demonstrated possibilities for significantly improving off-road mobility, and soft-ground performance in particular, beyond present military levels within a practical engineering, operational and economic envelope.

However, the total cost (in various coins, of which the dollar is only one) has been judged excessive in relation to the performance until recently thought to be required of our present tracked vehicle family.

The technology of terrain-vehicle relationships -- and soft-ground performance in particular -- has elucidated the fundamental relationships involved, and has clearly demonstrated that major improvements necessarily involve major changes in vehicle form (one of the "costs" referred to above); that there are no cheap answers. The basic level of off-road mobility of a new vehicle is accordingly frozen at that early point in its conception when its overall configuration is determined, and there is little positive that subsequent tinkering can accomplish. Largely for this reason, use of the available terrain-vehicle technology has been limited largely to preliminary concept and design studies, where it is in fact most appropriate in the design process. Unfortunately, the further basic message of the technology, that the level of a vehicle's ground-loading is indeed the most important single factor in its soft-ground operation, is generally ignored. New vehicle after new vehicle exceeds its "designed" empty weight by up to 50 percent or more, without change in its designed running gear, and with no person, organization, committee or consortium of committees being called to account.

Use of the available calculation methods in such early stages of design, but in no responsible way in relation to the final "hardware" product, has had two important, related consequences to the research effort.

First, the intrinsic correctness and precision of models and calculations (as distinct from their validity in assessing relative orders of merit of competing design concepts) have not been subject to the searching scrutiny which would automatically come with their use, for example, in relation to actual, testable performance specifications. This, in turn, has allowed a number of approximate concepts and incomplete and/or imprecise models to continue past their normal useful life, and has left the engineering research effort in a vacuum where it is encouraged to shadowbox with problems of its own invention. Considerable research has recently been started on vehicle off-road "ride," obstacle, and vegetation problems which aims at much higher precision than can reasonably be of use to the vehicle designer. From a vehicle design viewpoint, a fundamental reevaluation of the current soft-ground technology, aimed at validating a single set of soil values and vehicle-soil models, is still needed.

The situation is not fundamentally a technical one, or one which should concern terrain-vehicle researchers only, however. It is only one symptom of lack of proper organization and method in the overall military vehicle design system, from requirements to release for production. The current, committee-ridden process is characterized by a comingling of research and design, lack of

job division along sound professional and functional lines, and partly as a result, lack of technical performance specifications. In consequence, there are no clear lines of responsibility for various aspects of the success of the final product.

Our current family of military vehicles has been "optimized" -- albeit by informal procedures and perhaps without full realization of the geographic restrictions implicit -- for a conceivable war in Europe or North America. The discovery that it is so far from optimum for other large areas which now concern us -- the tropics and subtropics, and underdeveloped areas generally -- has precipitated a "ground mobility crisis." In the best American tradition, we are looking for a villain, and past terrain-vehicle research has been nominated. The results of this research surely have their shortcomings, but they have clearly and consistently shown that off-road mobility is a function of basic vehicle configuration and characteristics, and that improvement over present levels cannot be had without significant readjustments in currently accepted balances between conflicting desires for other features, important and trivial. These findings closely parallel the fundamental findings in ship and aircraft performance research over the years. Wherever these other "mobility" fields have accepted the implications of such results, in relation to ground-crawling machines they have been unpalatable, the research effort has been condemned, and the decision taken, with or without full systems analysis, that current compromises are optimum for the situation at hand -- implicitly, operations (conventional?) in developed, temperate lands.

The crisis atmosphere has fostered considerable nonsense about "special purpose" vehicles. This has wasted time and obscured the real problem, which is to create a new ground vehicle system, optimized for a new range of significantly more severe environmental conditions; a *second family* of vehicles, not intended to supplant current vehicles, or even to compete with them in their own areas of optimization, but rather to operate as an integrated system in broad areas where our current family is largely impotent. If we are serious about developing the capability for effective ground operations in these other areas, we must stop looking for cheap, gadgety answers. We must recognize that a collection of toys and assorted special purpose oddities will not do the job; that what is needed is a homogeneous second family of practical, flexible, reliable, military quality, working vehicles specifically designed to operate where our present family will not. And if the basic problem is as pressing as the crisis atmosphere would indicate, we must create the first generation of this family far more quickly than we have -- by trial and error -- arrived at our current optimum "European family."

This means that design must begin now, within the present state-of-the-art, and with the kind of urgency which had the first, still imperfect, *second version* of the WWII Weasel in the hands of the troops within 18 months from the time the need for a vehicle of this (then) radical new type was first suggested. Present technology would adequately support such an effort. Present peace-fat organizational procedures would not.

From the viewpoint of available technology, there would be little question of essential design priorities. The overriding design object

inescapably would be to gain an order of magnitude increase in off-road mobility. Currently accepted cost versus performance break-even points would all have to be relocated to an entirely new level. Present knowledge would permit a "first-cut" at a systems analysis to aid this relocation. This, and many other aspects of an ideal design procedure, would at this time necessarily include many "educated guesses" alongside indisputable data or models, and the resulting first generation would not be fully optimum. It would, however, reliably do most of the jobs which need doing, in vast areas where our current ground-crawling machines cannot now operate effectively.

Terrain-vehicle, environmental, and operational research results would all play their part in such a development, but clearly none could presently answer all the questions that would want answers. However, having once been asked the right questions within the framework of a real and pressing problem, and subsequently rewarded by "feedback" from unforeseen field experiences, all related research efforts would thereafter, and almost automatically, be put upon valid, fruitful paths, aiming toward a truly scientific systems analysis for the more accurate optimization of a further generation which would inevitably follow.

The second family question notwithstanding, the current state-of-the-art of design of military vehicles is fundamentally weakest in the meandering organizational process by which a field requirement eventually

becomes a vehicle ready for production. This situation exists whether or not the problem is to develop a new "second family" of vehicles, the next generation of the current European family, or a single special machine. In every case, strengthening this procedure is essential to timely progress, including the accelerated generation of valid, responsible terrain-vehicle research results.

In relation to ground-crawling vehicles, the objects of any alteration to present design and development procedures must be to reduce the time required to respond to a valid field requirement, and to insure that the hardware delivered does indeed meet it. Essential elements in a working system, lacking in the present process, are

- 1) clear separation of research and development activities from the "requirements" design line; i.e., a vehicle development should not be undertaken in this line unless the complete requirement, properly stated in quantitative engineering terms, is within current and realistically projected technology;
- 2) division of the work of the requirements line along sound professional and functional lines with definable interfaces; i.e., operational analysts should not design vehicles, design engineers should not have to become geographers, etc.; and
- 3) assignment of definable responsibility to each functional group with means to evaluate each group's performance.

One simple and somewhat obvious organizational scheme which might meet the basic requirements is diagrammed herein in elemental form (Fig 19). It illustrates a natural relationship in vehicle development between design for requirements, terrain-performance R&D and "idea vehicles," and component development, and proposes a clear division of responsibility along functional and professional lines. It would not require a sweeping reorganization of the Army, or of its general development procedures. Rather, the proposed scheme closely watches the current Army R&D organization. It envisions only certain simple but fundamental changes to assign clear responsibilities to various organizational elements, and in the process to limit the baleful influence of inter-organizational committee irresponsibility.

The first division proposed is to place responsibility for quantitative, functional vehicle specifications (only) entirely with an operational analysis group (perhaps within Combat Development Command (CDC)) who, in relation to off-road performance, would be required to provide, and be accountable for the adequacy of, testable off-road performance specifications. In the off-road design context, all environmental research would accordingly become of interest primarily to this group. This group would also be charged with setting forth a minimum set of design constraints from other considerations in functional form only.

The vehicle development agency, Army Materiel Command (AMC), would have sole responsibility for meeting in an optimum mechanical configuration the testable performance specifications within the given constraints, or for rejecting the job at the outset as beyond current technology. Terrain-vehicle research

would accordingly be conducted largely in support of the mechanical design effort.

Off-road performance testing would be conducted at two distinct levels, as now (Test and Evaluation Command [TECOM]). The first would be conducted entirely in relation to the testable performance specifications, and would determine whether or not these had been met by the design agency. These tests would automatically check the validity and accuracy of the terrain-vehicle relationships used in the design. If the first round of tests showed the vehicle to be satisfactory, it would proceed to other engineering tests of primary importance and to field tests -- along with the operational doctrine within which the testable performance specifications were conceived. The field tests would be conducted according to the supporting doctrine and would determine whether or not the vehicle and doctrine met the original functional requirement. In the process, the field tests would check the validity and accuracy of the terrain and operational models used.

Such a system could be expected to provide faster and more responsible response to many field requirements for vehicles by separating R&D from the specific requirements design line, and by establishing quantitative specifications which limit the power of across-the-board committees of changing personnel to meddle constantly with the work in progress. It would also force the supporting research on operations, on terrain-vehicle relationships, and on the environment, to operate in real time on real problems and to come up with real answers.

INTRODUCTION

In the beginning there was M225. The major object of the M225 study was to pull together, and where necessary extend, more than twenty years of research on ground mobility and terrain-vehicle interactions into a valid, usable, complete procedure to aid the vehicle designer in dealing rationally with the off-road performance of a new vehicle while it is still in its formative stages. Emphasis was placed upon the new order of off-road problems encountered in Southeast Asia where, quite simply, our standard ground-crawling military vehicles had by 1943 been found generally inadequate to provide the ground mobility required for the kind of operations our ground forces would like to conduct. The present evaluation of the state-of-the-art was made within this context.

Three notions fundamental to this study require brief elucidation at the outset: "ground mobility," "evaluation of the state-of-the-art," and "the vehicle designer."

Ground Mobility

Mobility is a quality of a vehicle in a given terrain situation, not of the terrain *per se* (cf. Grabau, 1945). The first specific research on off-road vehicle performance began during WWII. It grew out of the repeated "hogging" of military vehicles in Italy, Northern Europe, the Pacific Islands -- in fact almost everywhere around the globe where there were vehicles. This was a first-order problem of vast concern. Somewhere during its early stages, work on this problem in this country came to be termed "mobility research." In the context of this research a vehicle's "ground mobility" accordingly became synonymous with its ability to negotiate mud and to cross weak ground. This limited usage

generally persists to the present, albeit in highly qualitative form, in TECOM test procedures [cf. TACG 700-700, 1957] and in Army Tank-Automotive Center bid specifications for new vehicles [cf. REPD 47-22, 1962].

Schlier began complicating matters when, quite slightly, he expanded the term to include further important elements of the spectrum of possible vehicle-terrain relationships -- trees and hills and lumps and bumps -- and proposed in relation to ground vehicles that, conceptually at least, the average speed of a vehicle in a given terrain was the proper measure of its mobility in that terrain [Johnson et al., 1951]. This concept was shortly refined to incorporate the average speed "from A to B" based upon the straight line distance between A and B regardless of the actual path necessarily taken by the vehicle [Brooks, 1958]. In the past few years the self-descriptive sailing term, "speed-made-good," has been applied to the latter speed [cf. Grabau, 1965].

More general military parlance, however, assigns a broader meaning to "mobility," applying it as often to entire military units as to a single ground-crawling vehicle. Also, as part of the familiar military triumvirate "firepower, armor, and mobility," for example, it has a longer history. This broader, older meaning generally relates more directly to dictionary definitions for mobility which, most succinctly, boil down to "moveableness" [Buttall's *Standard Dictionary of the English Language*, 1951]. It involves both self-propelled and assisted motion of anything from a single soldier to a division or more with all its equipment. Even in relation to the single vehicle, this mobility encompasses both "automobility" and "passive mobility" [Lynde, 1959].

Recent years have witnessed a flood of further qualitative definitions of varying scope: mobility is the ability to operate in the off-road environment of a military vehicle [Bischoff, 1962]; mobility is a measure of a vehicle's ability to traverse, under its own power, the variety of terrain conditions found on the earth's surface in a minimum time and yet remain capable of accomplishing its mission [Bischoff, 1964]; it is the capability to move freely over the surface of the earth and not be stopped by natural or man-made obstacles, with adequate traction and ground clearance to ensure relatively free movement through mud and soft ground [Parker, 1963]; the capability to traverse all types of roads and adverse terrain to the maximum practicable degree consistent with either of the specified vehicle requirements [REPD 62-22, 1962]; the competence of a vehicle to perform its mission as measured by its best average speed over a route representative of the terrain where it will operate [AMCP 706-355, 1962]; mobility is movement faster than the enemy at any given time with net result of the movement being detrimental to the enemy [Molladay, 1965]; mobility of a vehicle-mounted weapon system is its ability in time and space "to concentrate, to envelop, to deny . . ." [Rice and Hatch, 1966]. That's what mobility is.

In October 1964, despairing to achieve a quantitative engineering definition, Bekker proposed that the word "mobility" be struck from the terrain-vehicle lexicon [Bekker, 1964]. And none too soon, for a full session of the January 1965 SAE Congress was devoted to "Mobility of Terrain-Vehicle Systems," a title suggesting a truly daring new concept, but which was in fact only a meaningless melange of currently fashionable words [SAE, 1964].

Despite Bekker's ingenuous suggestion, the term "mobility," and more specifically "ground mobility," will be used from time to time herein, in context of Bekker's speed-made-good concept, but generally without any attempt at actual quantification. It will also be used in self-explanatory combined form; i.e., soft-ground mobility, sand mobility, etc., to express limited aspects of a vehicle's overall off-road performance potential. It is still a useful word.

Evaluation of the State-of-the-Art

The state-of-the-art of design for off-road performance may be evaluated in terms of the extent, validity, rate of advance, and practical usefulness of the available technology, the rate of innovation in developing new mechanical solutions, and the performance and adequacy of the best current machines. Performance and adequacy of our best military vehicles may in turn be judged in relation to similar commercial and foreign military machinery; to some sort of envelope of technical feasibility; and, most importantly, to the jobs they are expected to do. In the present circumstances it is the high and nebulous expectations which appear most troublesome.

Our technological society has made us highly dependent upon our machines, and our world responsibilities and aspirations have made this particularly and painfully true in military matters. At the same time, as a nation, we have come to believe that science and sufficient research and development (R&D) can devise practical machines for any purpose. From the viewpoint of mobility, our ground-crawling machines appear to have let us down. Surely something can be done. Or can it?

The problem of expectations, indeed the overall problem of progress in military vehicle development, is far from being a new one. Thirty-seven years ago, in analyzing the faltering course of medium tank developments since WWI, the U. S. Army

Ordnance Committee concluded that progress had been impeded largely by a number of policy mistakes, abstracted as follows [OCM Item 7814, 1929]:

1. Lack of a definite War Department policy.
2. . . .
3. Dispersion of efforts and funds through the development of accessories before the basis of any tank, the chassis, was developed to a satisfactory state.
4. Making perfection in the experimental vehicle the criterion for standardization.
5. Too great a faith on the part of non-technical people in the belief that any difficulty can be overcome by research and development. ". . . in some lines science reaches an impasse, or at least a period of diminishing returns."
6. Too frequent changes in officer personnel.
7. Demands by the using services as to weight, speed, armor, and other qualities which are mutually incompatible and unattainable.
8. Frequent changes by the using service in the tank specifications laid down by it.
9. Entirely inadequate funds for the size and newness of the field to be covered.

While only item 5 is germane to the immediate discussion, the entire list, with minor modifications, could well serve as an outline for a discussion of current military off-road vehicle design problems.

The Vehicle Designer

The overall MERS goal of aiding "the vehicle designer" raises a final perplexing question -- just who is the designer of a military vehicle? To whom should a treatise on proper design for off-road performance be addressed? To whom dedicated?

Although the root of the problem lies in the nature of the terrain-vehicle relation ship, which is determined to an overwhelming degree by the fundamental configuration of the vehicle and by its scale in relation to nature, it is exacerbated in relation to military vehicles by a plethora of checks and balances ponderously operated by committees.* Accordingly, examination of the organizational processes by which military vehicles come into being necessarily formed a part of this study.

*The same is true, of course, in the design of ships and aircraft, but in these fields the technological bases for this are widely understood and accepted, as are the outlines of the envelope of technical feasibility within which solutions may reasonably be sought. The result is that ship and aircraft design objectives are more usually formulated in terms which allow scope for the accommodation of the finished vehicle to the laws of nature as well as to the desires of the requirements writer.

SOME HISTORY, ANCIENT BUT RELEVANT

Ground-crawling vehicles are of ancient lineage, and building their present technology has attracted the time and talents of many men over many centuries. The beginnings of concern with effective vehicle-terrain relationships must be dated from the inventions of the wheel and the road. Development of both proceeded on entirely pragmatic lines, however, until the 18th century. Bekker has traced attempts at mathematical analysis of wheel-soil interactions as far back as Grandvalet in the 1790's [Bekker, 1956].

By the turn of the 19th century, under pressure of the dawning age of industrial goods, improved overland travel was a glamour field, and many clever men were considering and proposing improved ground-crawling methods. Beginning with Edgeworth [1770], British (and later United States) patent files of the next one hundred and fifty years are replete with ingenious mechanisms to improve the flotation of ground vehicles and, after the practical advent of mobile steam power in the early 1800's, their traction as well [Young, 1860]. Much of the concern was for protection of earthen roads rather than for the improvement strictly of off-road performance, but the distinction between roads and nonroads was then often problematic [Legros, 1910].

Frequently the concepts proposed were far ahead of other necessary supporting technology, and failed in their time. However, many have a very up-to-date look in the space age. The modern

notion of ground pressure was often explicit in their development. Rickett said of his proposed elastic metal wheels (1842), "The object of this invention is to facilitate the movement of locomotive engines and other carriages, more particularly over soft or uneven ground, by giving to them, through an elastic medium, a more extended bearing surface on the ground."

The similarity of on-road and off-road problems, which as late as 1900 appeared to contemporary engineers to show little sign of ending [Hole-Shaw, 1900], did in fact dwindle rapidly with the advent of the private automobile and the accelerated construction of paved roads. While the commercial "on-road" traction engines of 1880 were reasonably adapted to military use in the Boer War [Layriz, 1900], on-road and off-road practice had so far diverged by 1915 that when it came time to "invent" the tank, the British called upon American farm tractor manufacturers for their first successful tracked running gear [Stern, 1919].

Dwarfed by the post-WWI on-road vehicle explosion, off-road vehicle developments for farm and construction work borrowed much from the rapidly advancing on-road vehicle technology and capitalized upon the general march of technology as well. While this, and their basic ground-crawling function, led to many resemblances between on- and off-road machines, they are, at the fundamental level of their vehicle-terrain interaction, quite different, even in many important respects unrelated. This was recognized in the 1929 Ordnance Committee analysis of medium tank development, already alluded to, in which it was pointed

out that a tank is as distinct a vehicle as an aircraft. Unfortunately, this basic fact is still not clear to many today.

Thus by the 1930's there had been considerable activity in off-road vehicle development over many years. Many vehicle configurations and mechanisms had been tried, many more proposed. Most had been conceived within a broad understanding of the nature of the off-road problem, and of the directions in which feasible solutions lay. Grandvalet had been succeeded over the years by Morin [1840], Bernstein [1913], Randolph [1927], Goriatchkin [1936], Letoshnev [1936], and others in the analytic treatment, based upon simplified soil models, specifically of vehicle-soil interactions. At mid-decade the farm tractor industry undertook a program of systematic tests of tires [SAE Cooperative Tractor Tire Testing Committee, 1937]; McKibben had begun his pioneering research on agricultural tires [1938, 1940]; and here and there, as in the Egypt Corps or Arabia (R. C. Kerr) or Longview, Texas (R. G. LeTourneau), men were discovering the potency of large pneumatic tires for big off-road jobs.

World War II quickly showed there was more to be learned. Under the impetus of tank and truck immobilizations in the mud of a worldwide war, organized systematic study of the vehicle-versus-mud and weak soil problem began in Great Britain (Committee on Mud Crossing Performance of Tracklaying Armoured Fighting Vehicles: Hoad, Micklethwait, Markwick, Sherratt, Evans, et al.); in the United States (SAE War Emergency Tractor Committee and the Ordnance Corps: Norelius, Churchill, Cross, Elliott, Wilson, et al.; and the Engineer Board:

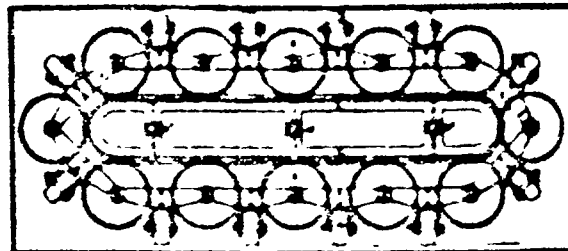
Engler, Ekland, Kerr); and in Canada (National Research Council: Leggett, Bekker). This "crash" activity produced several basic and still useful concepts on vehicle-soil interactions, a few mobility "fixes" on then current machines, and one valid, working design guide, "The Influence of Load and Inflation on the Selection of Pneumatic Tires for Military Vehicles" [Ekland, 1945]. Its most profound influence, however, was to light the fuse for this line of engineering research, which is still sputtering.

At war's end, four basic approaches were in evidence. In Britain, civil engineering soil mechanics was utilized as the foundation for semi-empiric analyses of vehicle sinkage behavior in clay soils [Sherratt, 1945; Sherratt and Evans, 1946]. In the United States, the Engineer Corps was beginning from the same civil engineering base to construct its closely documented, empirical cone penetrometer system for predicting soils trafficability [WES, 1945]; and the (then) Ordnance Corps had begun support of a modest study of the application to vehicle-soil problems of dimensional analysis [Muttall, 1949]. In Canada, Bekker was undertaking to formulate solutions in terms, synthesized from Terzaghi, Bernstein, Coriatchkin, Michlethuis, and others, which appeared to him more appropriate to simple analytic treatment of the soils problem posed by vehicle actions [Bekker, 1948]. Unfortunately, the several approaches utilize different soil value systems and different instruments for characterizing soil strength: the British shear vane [Evans, 1950], the WES cone penetrometer [TE ENG 37, 1959], and the two-part, penetration and shear, bevmeter [Pavlica, 1961].

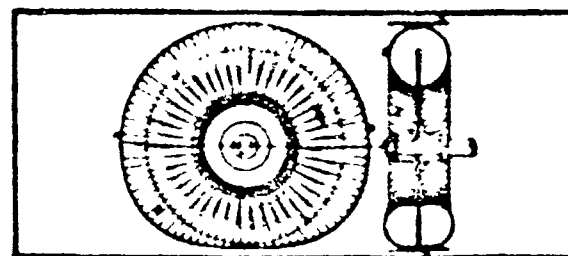
THE OLD



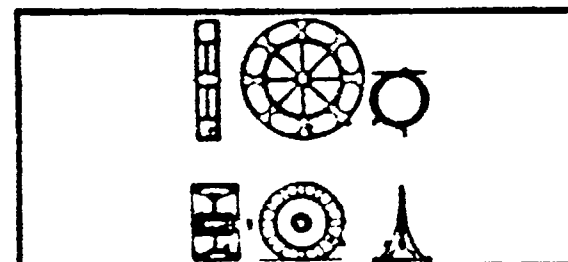
Gordon, 1801



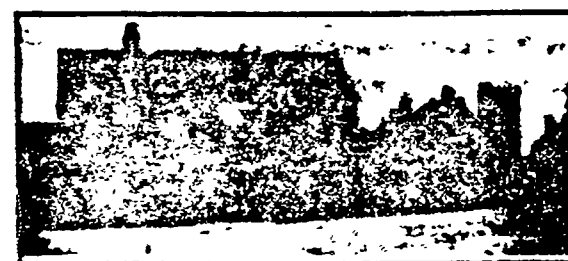
Pidding, 1846



Richett, 1858



Richett, 1858



Fowler, 1800

While each approach and its supporting soil value system and instrumentation has somewhat to recommend it in the beginning, and all have led, in the broad view, to quite similar results (as they must if at all correct), much of the work of many years following was conducted more in the spirit of a ladies' wrestling match than of scientific inquiry. At this moment, some twenty years after the opening bell, there is still no one validated and accepted soil value system for vehicle-soil studies.

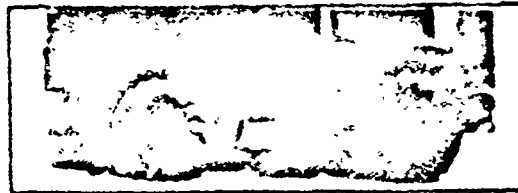
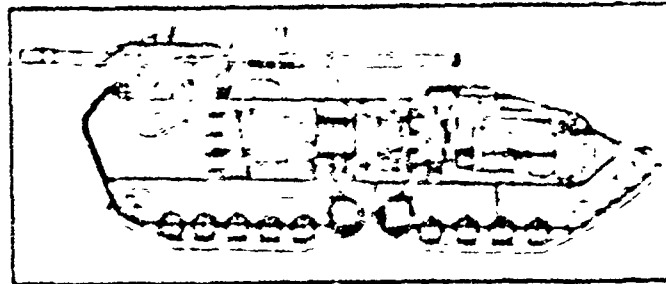
This is not to say that these years were unproductive. British investigators are satisfied that their current methods produce reasonable results for wheels and tracks in consolidated clay soils [Uffelman and Evans, 1965; Reece, 1965]. The Corps of Engineers cone penetrometer work (conducted since 1945 at WES) by 1956 had achieved its basic goal of predicting fine-grained soil trafficability in relation to existing vehicles by contact means [Knight, 1956; Knight and Rula, 1961]. Its cone penetrometer approach has since been extended to successful contact prediction in sands [Rush, 1959, 1961, 1963; Freitag and Knight, 1963] and snows [Rula et al., 1955; Blackmon and Rula, 1960], and to promising preliminary contact studies in organic soils [Schreiner, 1965]. It has also been the basis for developing methods for forecasting soils trafficability [cf. Carlson, 1959], for a sound beginning of the much needed generalization of surface soil strength information on a geographic basis [Turnbull and Knight, 1961; Meyer and Knight, 1961; Meyer, 1966], and for studies of means to determine trafficability by noncontact methods using remote sensors [Davis et al., 1965, 1966; Davis, 1966]. The cone penetrometer has also proven useful as the basic soil measurement instrument in dimensionally

oriented, meticulous, systematic studies and analyses by WES of tire performance in both sands and clays [cf. Freitag, 1965; Smith, 1965; Turnage and Green, 1966], and in a preliminary field program to develop means to extend the 30-pass soil trafficability to the prediction of first-past performance [UNRRL, 1965]. Bekker's approach to soil-vehicle interactions has been espoused by the U. S. Army Tank-Automotive Center (ATAC), where its refinement and elaboration and its application to design analyses have been a major concern of the Land Locomotion Laboratory, founded by Bekker in 1954 [Liston, 1965]. It has also been adopted by NASA as the system for specifying moon soils, and for designing and evaluating moon vehicles [cf. Pavlica, 1964; Wong and Galan, 1966].

Only the fundamental dimensional approach has lacked clear continuity. However, despite some embarrassingly bad work in its name [Clark et al., 1965], it has in the past few years shown signs of quietly becoming a mainstay of current work at both ATAC [cf. Liston and Hegedus, 1964] and WES [cf. Freitag, 1965], and is beginning to occupy a leading position in the vehicle-soils research at several agricultural engineering colleges [cf. Clark and Liljedahl, 1965; Huang et al., 1964; Olson and Weber, 1965; Siemens et al., 1965; Pierott and Buchele, 1966]. There are currently some 21 organizations in this country and Canada having indoor soil bin test facilities for the study of equipment-soil problems (Appendix I). Most are involved in one way or another with the dimensional approach, and fully recognize the fact.

AND THE NEW

Cobra II, 1951

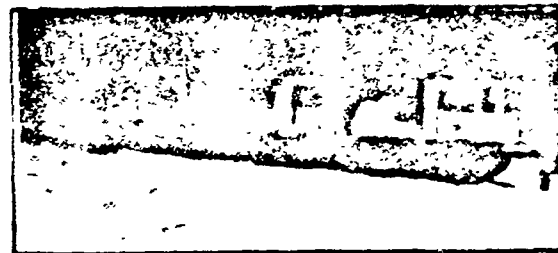


Jumbo Truck, 1959

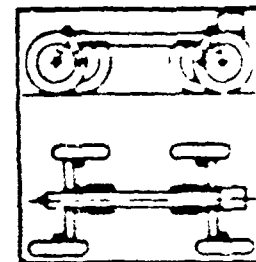


AARAF T Proposal, 1959

Cobra ATAC, 1959

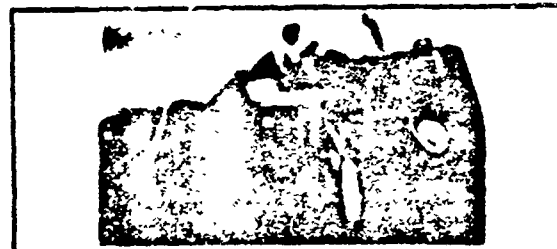


Cobra Goat, LTV, 1959



Schroter, 1951

8010, Deere, 1962



THE TOTAL OFF-ROAD MILITARY VEHICLE ENVIRONMENT

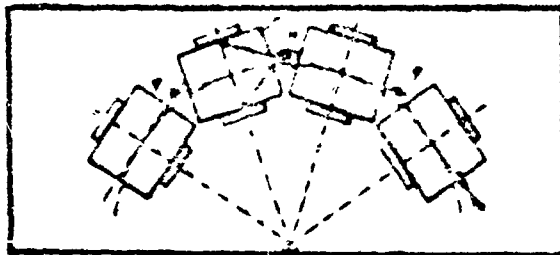
Although the research on terrain-vehicle relationships began with consideration of the first-order problem, to-go or not-to-go in mud and weak soils, the extended problem, including obstacles, roughness, vegetation, etc., is now widely under study. Moreover, in considering the design of off-road military vehicles, still other elements enter. The resulting assemblage may be termed the total off-road military vehicle environment. It may be considered to consist of the combined effects of climate and personnel as well as terrain. Some conception of its overall severity is given by the fact that standard Army trucks have a life of approximately 20,000 miles, while the life of less rugged commercial road vehicles is normally reckoned in 100,000's of miles [Lynde, 1958]. Put another way, fully developed commercial trucks in nominally similar use by the military have a reliability of only 30-40 per cent at 20,000 miles, where the current overall target for tactical military trucks is 90 per cent [AMCP-706-134, 1961].

Climatic, even microclimatic, components of the environment per se are generally diffuse, and are normally treated as relatively long-term phenomena (cycles and statistically expressed measures of rainfall, temperature, humidity, radiation, etc.). Short-term manifestations, such as heavy rainfall, however, can have profound effects, sometimes directly (as on visibility), more often indirectly (as through changes in current soil mechanical properties).

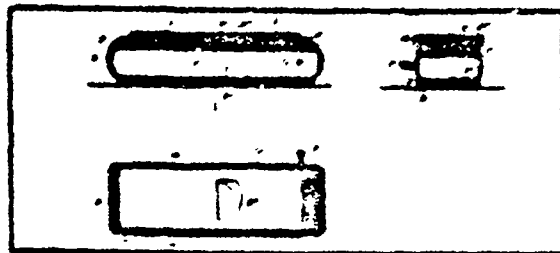
The personnel component is more frequently manifested by general abuse of vehicles than by training in their intelligent exploitation. Effects tend to be Army-wide. They vary markedly with troop morale, training, some as yet undefined sex appeal (or lack thereof) of a particular vehicle design, and perhaps the tactical situation. Thus far the personnel component appears to vary only in secondary and derivative fashion with geographic locale. Its effects, however, can overshadow all others. In extreme cases, personnel behavior essentially unrelated to the particular physical environment can almost totally obscure the effects of other environmental inputs.

The factors which describe the terrain segment of the environment are of two kinds: those expressing relatively stable, long term attributes, and those expressing the immediate state of elements subject to seasonal and/or daily variation. A vehicle's performance is influenced by the geometric and mechanical features and properties it finds point-by-point and moment-by-moment in the terrain. These, in turn, reflect the combined effects of both types of factors.

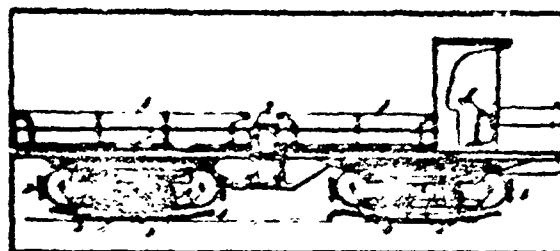
A slope is a slope. Consider one of reasonable length and uniformity, extreme but not impossible -- say one having a 30-percent grade. Whether or not a given, relatively mobile vehicle will negotiate it depends on many other factors acting in concert with the slope. All may be considered, for general design purposes, to be independent. It is readily apparent, for example, that the type or types of soil involved, their stratification and moisture content, the extent of superimposed minor relief (microrelief), the surface



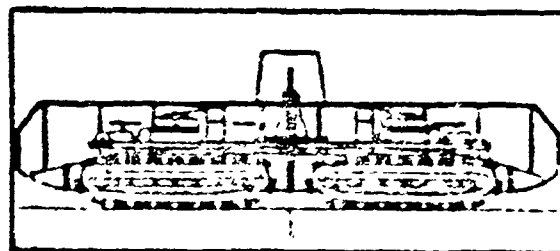
Diplock, 1903



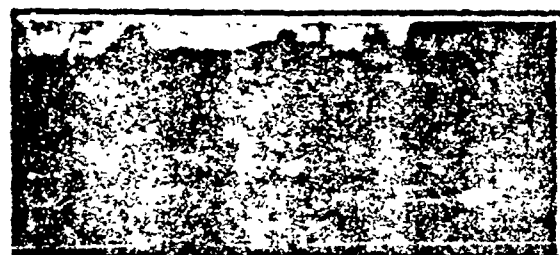
Furchter, 1906



Diplock, 1914



Suter, 1915



Landship Committee, 1916

roughness (microrelief), and the kind and condition of vegetative cover may each have some influence.

Slope (macrorrelief), soil type and stratification, general vegetative cover, microrelief, and perhaps microrelief are relatively stable. Soil moisture content and its stratification will usually vary from day to day; the state of vegetation, from week to week. All will vary in more-or-less degree at different points in the vehicle's travel even in a nominally homogeneous terrain, and most will be altered to some extent by the vehicle's passage.

The long-term factors -- topography (macro-, micro-, and mini-), the general vegetative picture, soil types and distributions, overall ground water regime, semipermanent cultural features, etc. -- may for the most part be considered on the basis of relatively large areal units. They may usefully be analyzed and classified for design purposes essentially within the framework of classical naturalistic studies. The variable attributes must be treated on a time-dependent basis, reflecting temporal variations in weather, cyclic influences of climate, the mechanics of soil moisture and plant growth, and the onslaught of mankind.

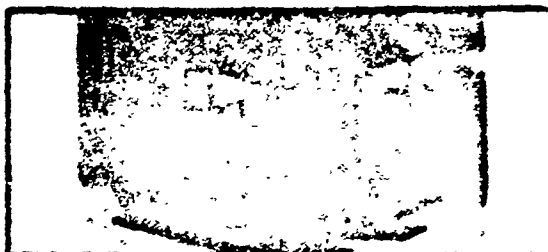
In the aggregate, proper, long-term, broad classifications -- in terms of landform, geology, ecology, climate, etc. -- with their interrelationships, constitute the only sound base for predicting conditions to be found in unsampled (and sometimes unsamplable) areas of the world, and hence for predicting equipment performance (or, conversely, requirements) in such areas. The considerable environmental research which must be done to

develop this potential, via the correlation of the naturalistic classification systems with the occurrence of geometric and mechanical features which directly affect the performance of military equipment, appears to be one of the essential steps necessary to the development of more rational design approaches.

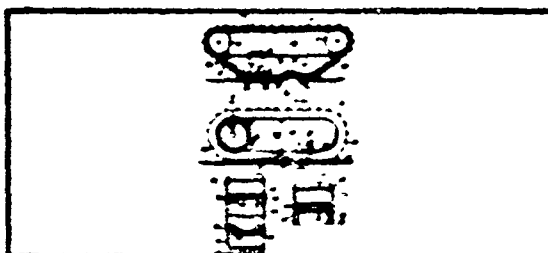
LeTourneau 1963



Marsh Equipment Co 1963



Berteles, 1963



Marsh Screw, Chrysler, 1963



USATB, 1963



VEHICLE-TERRAIN RELATIONSHIPS GENERALLY

By the definition accepted for this study, mobility is essentially speed; speed in a straight line or "speed-made-good" toward an objective when a straight line is impossible or impractical. All phases of its study (with the exception of terrain roughness) have both "go, no-go" and speed aspects. In theory, at least, a usefully complete treatment of mobility should consider the full range of speeds from zero (no-go) on up to the practical operational maxima for various conditions as determined by the total terrain-vehicle relationship.

A given vehicle's performance in a terrain at any moment is a function, insofar as the terrain is concerned, primarily of the geometric and mechanical features and properties of the small area the vehicle occupies at that moment. The most seemingly variegated terrain may be broken into manageable increments of reasonable homogeneity for detailed treatment, and subsequently integrated to obtain a final figure for a total traverse. Moreover, study and prediction of any and all primary facets of off-road performance are problems in engineering mechanics, basically simple, but made complicated by the intrinsic complexity of both vehicle and terrain geometry.

In order to facilitate study, the complexity of the overall problem is arbitrarily reduced by isolating various kinds of vehicle-terrain interaction for individual, simplified treatment. The assumptions are usually tacitly made that in the more complex incremental situations found in nature separate effects may be combined essentially by superposition, and that the order of improvements

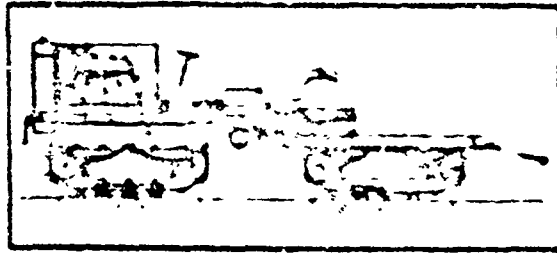
in performance in the simplified situations will be reflected in corresponding field situations as well. Although not strictly true, these have proven to be useful in clarifying the complete picture and for design and gross estimating purposes. Moreover, relatively "pure" situations, in which one simple type of vehicle-terrain interaction essentially controls, are not uncommon.

The current division of the vehicle-terrain problem (cf. Lister, 1952; YECF 700-700, 1964; Wisner, 1965; Grabau, 1964, 1965) treats the terrain separately in terms of

- 1) its surface materials -- the soft-ground problem,
- 2) its major topography -- the slope problem, and
- 3) its minor surface geometry -- the obstacle problem.

It is convenient to still further divide consideration of terrain obstacles (3) according to the kinds of vehicle response they produce:

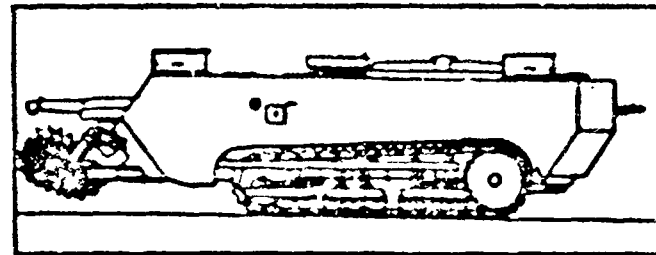
- a) continuous ground roughness, which results in essentially continuous but random vibrations of and within the vehicle, and which the driver manages as a persistent element of his environment whose level he adjusts through speed control;
- b) essentially singular obstacles, each of which presents a separate challenge to the vehicle's progress because of mechanical interferences, excessive traction demands, and/or the development of extreme motions and/or dynamic forces on and in the vehicle, and which the driver must deal with essentially one-by-one; and



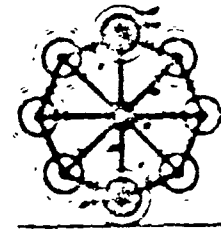
Diplorh, 1917



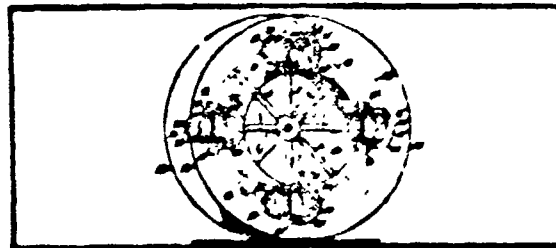
US Army, 1918



Saint-Chamond, 1918



Macbeth, Paull, 1919



McDermott, 1921



Pavesi, 1922

c) planimetric arrays of obstacles which are insurmountable by a given vehicle, and which may or may not be penetrable through maneuver. Major components of vegetation normally fall in this category.

Obviously, subclassification of a particular segment of terrain geometry in these latter terms will depend upon the relative scale of vehicle and terrain features, and, to a lesser extent, upon the general characteristics of the vehicle. Conceivably the same boulder field could be merely roughness to a very large vehicle, present a succession of critical, singular obstacles to a smaller one, and offer a field of insurmountable obstacles to a tiny one. It is to be noted, however, that a full quantitative depiction of its three-dimensional geometry would provide the basic data for studying all of these cases.

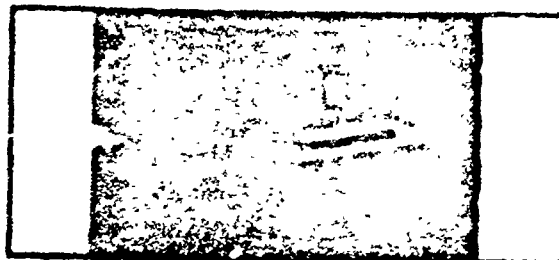
Finally, there are a number of characteristics peculiar to vegetation which sometimes influence practical mobility. First and most important, vegetation often limits driver vision, obscuring obstacles, imposing difficulties in route selection, etc. Another characteristic is its resistance to being overridden by a vehicle, and a third is the potential of vegetation to contribute to the bearing strength of the ground surface, /or to its surface slipperiness.

THE PRESENTLY AVAILABLE TECHNOLOGY

The technology on terrain-vehicle relationships presently available for the design of off-road, ground-crawling vehicles falls into categories paralleling those just discussed. The soft-ground problem and the slope problem are treated by vehicle-soil mechanics stemming directly from the wheel roots. The terrain roughness problem is under study by means of important extensions of automobile "ride" technology. Serious study of singular obstacles and planimetric arrays of obstacles, and of troublesome aspects of vegetation, is essentially young but able. The entire technology has since about 1963 been uneasily embraced along with related aspects of earthmoving and agricultural equipment mechanics, by the single term "terramechanics."

A significant but partially intangible asset to the state of the technology is the existence of the International Society for Terrain-Vehicle Systems (ISTVS), founded in 1962, following the fruitful "First International Conference on the Mechanics of Soil-Vehicle Systems," held in Turin, Italy, in June 1961 [ISTVS, 1961; also, Ogorkiewicz, 1961]. ISTVS was formed "to effect the achievement and advancement of knowledge of the mechanics of terrain-vehicle systems and soil working machinery in all environments." As of early 1966 it had 134 U. S. members and 135 from 19 other countries, including two behind the curtain. While the U. S. membership is predominantly from the military R&D establishments involved in vehicle problems, and their contractors, some 90 percent of the non-U. S..

BY 200 Bunker Model 1 1961



Blumartini, 1964



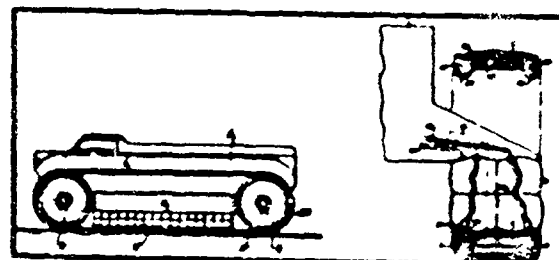
Airroll, USMC, 1964



MARV, GMRDL, 1964



Hardy, 1964



membership is made up of university researchers in agriculture and construction and professionals associated with commercial operations. Approximately 80 percent of the total membership is involved in research and development of some sort.

Beginning in 1964, ISTVS has sponsored a substantial quarterly, the *Journal of Terramechanics*, ably edited by A. R. Reece, of the University of Newcastle, U. K. In August 1966 the society held its second international conference in Quebec City, Quebec. The accumulated file of the *Journals*, the *Proceedings* of the Turin and Quebec conferences [ISTVS, 1961, 1966], plus the papers presented at a series of specially organized sessions on ground mobility at three consecutive Society of Automotive Engineers (SAE) congresses, 1963, 1964, 1965 [see SAE, 1964], and the 1965 Institution of Mechanical Engineers Symposium on Earth-moving Machinery [IME, 1965], Eklund's 1945 report and some 25 recent NES reports listed in Appendix II, provide a good working bibliography of the current technology available to the designer.

The SAE series adds a further and necessary dimension, systems analysis, to the overall technology. And in its train, systems analysis implicitly brings the need for quantified and generalized terrain information on a large scale, and often for areas where contact procedures for obtaining it are interdicted. These are the problems of environmental research. The cast is now complete, and the die is cast.

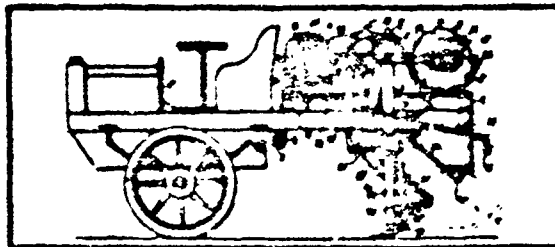
Vehicle-Soil Mechanics -- Debts

Vehicle-soil mechanics is the master link of the entire chain. In the complete quantitative systems approach now being forged, it is also the weakest. While it is generally conceded that the 20 years of accumulated research have contributed usefully to qualitative understanding of vehicle-soil relationships [cf. Ogorkiewicz, 1962], it has yet to reach the goal of "quantitative understanding of the performance of vehicle running gear in simple soil systems" enunciated by Rees in 1963. In fact, it must be agreed that, quantitatively, "... the ability to predict vehicle performance is very poor . . ." [Jones, 1965].

Most under the gun, because of the long continuity of their supporting research, their wide publication, and the claims made in their behalf, are the simplified analytical methods and associated soil value system based upon Bekker's pioneering early work (1956, 1960). Their current status was summarized by Bekker in his James Clayton Lecture before the Institution of Mechanical Engineers (1963). In the past 12 years Bekker's approach has been carried forward largely by the ATAC Land Locomotion Laboratory (LLL). As developed by LLL, the system has departed somewhat from some of Bekker's earlier simplifications, and is now generally referred to as the "LLL System." Nonetheless, the specific accuracy with which such simple and fundamental performance measures as the drawbar pull of existing pneumatic-tired and tracked vehicles in measured soil conditions may be calculated by this system has been poor [Wheel Track, 1963; Clarke, 1965]. Rees (1964) concluded after a full year's



US Army, 1922



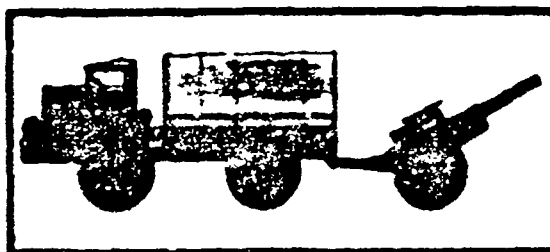
Ehrlich, 1926



Christie, 1936



1936



Storey, 1939

exposure to the on-going LLL research that "... Bekker's system is not a scientific theory but a hypothesis." As late as 1963, in beginning systems studies on combat tanks at Ohio State University, it was decided, after reviewing the situation, to start effectively from scratch to develop means to calculate the performance of tracked vehicles in weak soils [Perloff, 1963, 1964]. Criticisms of the details of the LLL concept are at least as numerous [cf. Little, 1962; Porrucci, 1963; Reece, 1964, 1965; Arsur, 1964; Willis et al., 1965; Nverslov, 1965; Reece and Willis, 1965; Cleare, 1965; Vodyanik, 1965; Reece and Adams, 1966; Willis, 1966].

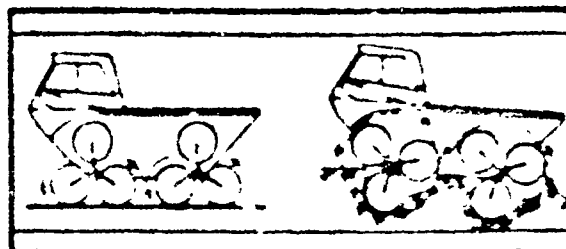
The weaknesses of the current LLL system are recognized by LLL both directly [Liston, 1964] and indirectly, in their continuing support of and requirements for further, more basic soils research [cf. AMC-QDRI, 1965]. The system is ably defended, however, as the most advanced, practical, promising, and quantitative available, and as providing reliable estimates of the relative soft soil performance of an array of vehicles [Liston, 1964]. The LLL system is also considered as an adequate basis to begin needed system analyses [Bekker, 1964]. The necessity to express soil and vehicle parameters, and their relationships to measurable vehicle performance, in quantitative terms cannot be denied. The LLL system does provide mathematical models so necessary to modern computer studies. Moreover, the models are sufficiently complex to give such exercises the test of an analysis requiring modestly advanced systems and mathematical techniques. Whether or not, in the face of the imprecision of the basic models, such analyses have meaning beyond demonstrating what might be done with proper models, is another question.

LLL is not alone. Although the British generally concede that their solutions for wheels and tracks in consolidated clay soils are basically sound [Reece, 1963; Uffelman and Evans, 1963], accuracy is poor when slip and/or sinkage becomes appreciable [cf. Reece and Adams, 1962; Willis et al., 1965]. And the venerable WES empiric equation for estimating the strength of fine grained soils (in terms of cone indices) needed for the trafficability of pneumatic-tired vehicles unburn, or at least untested [Knight, 1956], continues to be revised regularly as the realities of further vehicles are encountered [cf. Rush, 1962; WDEA, 1963; Rush and Schreiner, 1966].

Of the 10 year-old WES program in the vehicle-soil mechanics aspects of ground mobility research, as distinct from their trafficability research, it can only be said that the cumulative results are becoming impressive [cf. Green et al., 1964; Freitag, 1965] but are essentially unvalidated by design application or in independent field trials.

Finally, the current state of fundamental understanding of soils and soil-vehicle relationships is such that, despite many attempts beginning in 1944 [Markwick], the first-order problem of formulating definitive, accepted, reasonably complete dimensional analyses of various types of soil-vehicle behavior is, in effect, still in abeyance. While this gap is most apparent in relation to dynamic soil-vehicle relationships, there is not even a clear consensus on static analyses [Muttall, 1949; Willetts, 1954; Muttall and McGowan, 1961; Vincent et al., 1963; Schuring, 1964; Liston and Megedus, 1964; Sullivan, 1964; Freitag, 1965; Goodman et al., 1966]. At the root of the problem, again, is the lack of a validated and accepted system of soil values.

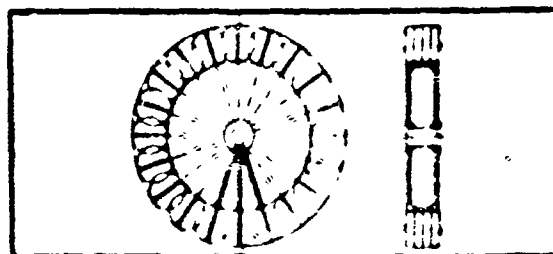
Lockheed, 1964



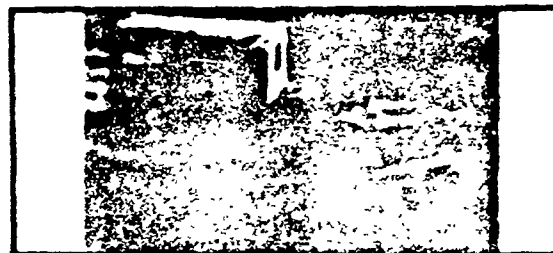
Grumman, 1964



Bendix, 1964

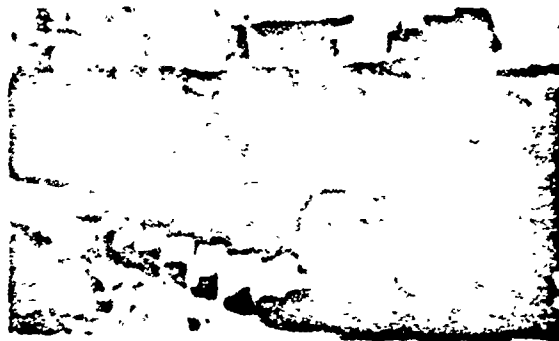


TREE FARMER, Canada Car, 1964



PATA, LTV, 1964





Japanese 1941



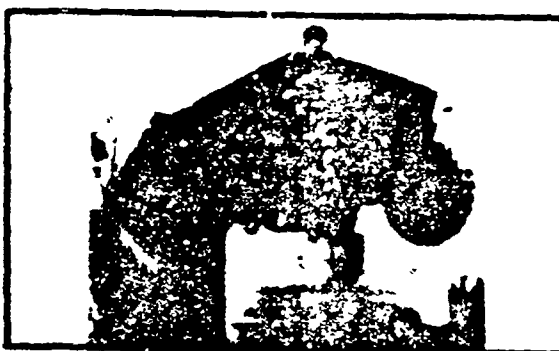
Weasel, 1941



US Army T23, 1944



Firestone 1954



M4 Sherman 1959

A dimensional analysis is an incomplete analysis, mathematically simple to perform. Although it is an indispensable tool in planning scale-model tests and interpreting their results, the true importance of a dimensional analysis lies in the fact that it demands the same degree of basic understanding of the phenomenon under study as does any more complete and powerful analysis of equal validity and refinement. The measurable properties of the overall soil-vehicle system used in formulating the one must be identically those used in the other. For this reason, dimensionally oriented experimentation, exploiting scale change as a major controllable variable, can be a particularly powerful means to study the validity both of general soil-vehicle concepts and of proposed soil value systems. If the validity of a dimensional analysis cannot be satisfactorily and widely demonstrated, neither can that of any more formal analyses starting from the same premises.

In retrospect, it is evident that the development and verification of basic dimensional analyses of soil-vehicle problems should have been the first order of this business. Much of the conflict, confusion, and lost motion of the past 20 years can, in fact, be traced to the fact that the relatively unprepossessing dimensionally-oriented research which could have provided needed clarification of the fundamentals of soil-vehicle interaction did not receive the support that apparently more direct and glamorous approaches did.

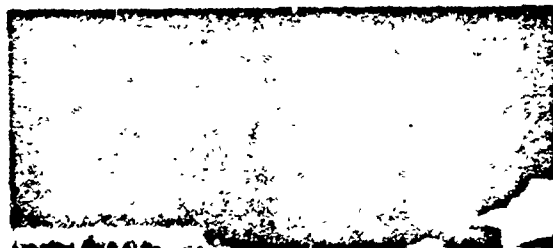
Vehicle-Soil Mechanics -- Credits

Despite the consensus that much of the present technology is inadequate to calculate accurately the soft-ground-crossing performance of vehicles, there are many bright spots. First, several different investigators have shown that the primary soil strength parameters measured by the devices employed in the several systems -- the cone penetrometer, the shear vane, the bevanmeter plate/shear tester -- do correlate reasonably well with one another and with standard civil engineering soil strength determinations [cf. Janosi, 1959; Smith, 1962, 1964; Osman, 1964; Buchele, 1964; Bailey and Weber, 1965]. Second, the several approaches may be shown to converge in rather simple terms and to have a degree of correlation in their assignment of relative performance potentials to an array of similar vehicles which is remarkable in light of the heat of past controversy, and the complexity of soils, both real and imagined.

As an example, which will be put to further use in a following section, simple soft-soil performance indices for pneumatic-tired vehicles are developed in Appendix III, utilizing the following currently published information:

- 1) The Eklund Mobility Factor [Eklund, 1965]
- 2) The WES 50-pass trafficability criterion [VMEA, 1965]
- 3) The WES sand tests [Freitag and Knight, 1963; Freitag, 1965]
- 4) Preliminary WES clay test results [Freitag, 1965]
- 5) Preliminary first-pass trafficability criterion [VMEA, 1965]

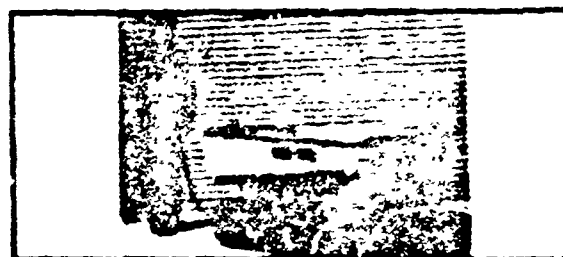
FOREMOST Nodwell 1965



Shendan. USATAC, 1965



TPAG-PAC 1965



M116, 1965





General Electric, 1965



USATAC LLL/GE, 1965

6) The FYWZ equations for rigid wheels in clay [Uffelmann, 1961]

7) The ILL soil value system and soil-vehicle model [Harrison et al., 1959]

The results are summarized in Table I. In these simplified expressions it is apparent that there is considerable basic consistency in the results from the several nominally competing sources. In clay soils, all other things being equal, reduction in the nominal unit ground pressure (NUGP) of a tire^a will clearly extend its range of operation into weaker soils no matter whose method is used. Moreover, there is across-the-board agreement that the same NUGP on vehicles in different size classes will result in the same order of performance of each in field clay conditions where the soil strength is uniform with depth. The results of WES trafficability fieldwork agree well both qualitatively and quantitatively with laboratory and analytical treatments, despite the fact that the field test results reflect complicating factors such as soil remolding and stratification, and the effects of multiple wheel behavior.

^aArbitrarily defined throughout this report simply as

$$NUGP = W_1 / br \quad (III-0.1)$$

where W_1 = average load on a single tire (lb)

b = undeflected tire section width (in.)

and $r = d/2$ = undeflected tire outside radius (in.)

In sands and sandy materials, $NUGP$ is again the controlling factor.* There is also good agreement that in these soil types larger vehicles (or larger tires) may operate at higher nominal unit loadings without loss in performance relative to smaller vehicles (or tires) at correspondingly lower loadings.

The results are, of course, in general agreement with many published dimensional analyses, starting with that by Markwick (1944), which have proposed that various dependent dimensionless performance measures of a wheel, or tire, or track, in soils, such as drawbar pull ratio (D/W) or sinkage ratio (s/d), were functions of the soil-vehicle systems numerics

$$W/c^2, W/\gamma d^3, \phi^{**}$$

plus some dynamic terms.

They also constitute a sound and useful design tool, whether they lend themselves to elaborate systems analyses or not. As a matter of fact, ATAC has utilized a nominal unit ground pressure which is

$$NUGP_{ATAC} \approx 1.1 NUGP$$

in vehicle design specifications and studies for several years [of. REPD 62-16, 1962; Wheel Track, 1963].

*The well-documented fact [of. Ekland, 1945; Shields, 1954] that tire deflection plays a major role in the performance of tires, particularly in sand, is accounted for in setting up the indices (App. III) by assuming that all tires are operated at a deflection equal to 25 percent of section height.

** c = soil cohesion; γ = soil density;
 ϕ = angle of internal friction.

TABLE 1
A COMPARISON OF SOFT SOIL PERFORMANCE INDICES
See Appendix II for details

SOIL TYPE	BASIC SOURCE	FORM	UNIT
CLAYS	1 PVBM - rigid wheels with sidewall traction - the larger of: or	$C_{PVBM} = 0.250 \text{ WUCP} [1 + 1.2775]$ $C_{PVBM} = 0.204 \text{ WUCP}$	psi psi
	2 PVBM - rigid wheels without sidewall traction	$C_{PVBM} = 2.500 \text{ WUCP}$	psi
	3 LLL - rigid wheels (no sidewall traction) $\alpha = 0$	$C_{LLL} = 0.500 \text{ WUCP}$	psi
	$\alpha = 0.5$	$C_{LLL} = 0.400 \text{ WUCP}$	psi
	4 VES - single tire in the laboratory	$CT_{VES} = 2.5 \text{ WUCP}$	psi
"FINE GRAINED SOILS"	5 VES - 50-pass trafficability, from field tests	$VCI = 4 \text{ WUCP} + 14$	psi
	6 VES/VMEZ - 1st-pass trafficability, from field tests	$VCI_1 = 3 \text{ WUCP} + 5$	psi
A SANDY LOAM	7 LLL - rigid wheels (no sidewall traction, $\text{WUCP} = 4.85 \text{ psi}$):	$E_{LLL} = \text{WUCP}(2/d^{0.5})$	$1b/1a^{0.5}$
"OPTIMUM"	8 Shind:	$H_0' = \text{WUCP}(2.2/c^{0.05})$	n.d.
SANDS	9 VES - field results:	$C_1 = \text{WUCP}(6/b^{0.5}d^{0.5})$	psi/in
	10 VES - single tire in laboratory:	$C_2 = \text{WUCP}(6/b^{0.5}d^{0.5})$	psi/in
<p>NOTES: $\text{WUCP} = U_1/b$, where U_1 = (average) load on a single tire (lb), b = undeflected tire width (in), d = d/I = undeflected tire outside radius.</p> <p>C_{PVBM} = minimum cohesion of soil at which vehicle will just maintain headway in unaccelerated, level, straight-line operation.</p> <p>CT_{PVBM} = minimum average cone index at which vehicle will just maintain headway in unaccelerated, level, straight-line operation.</p> <p>VCI = minimum average rating cone index of field soils at which vehicle will be able to make a minimum of 50 passes in the same rate in unaccelerated, level, straight-line operation.</p> <p>VCI_1 = minimum average rating cone index of field soils at which vehicle will just be able to maintain headway in unaccelerated, level, straight-line operation.</p> <p>E_{LLL} = minimum soil consistency in selected sandy loam ($\alpha = 0.5$, $\phi = 0.10$, $\tan \phi = 0.11$) at which vehicle will just be able to maintain headway in unaccelerated, level, straight-line operation.</p> <p>H_0' = Inverse Shind Mobility Factor (modified and not in percent) which is the ratio of actual tire loading to suggested optimum loading derived from combined performance and tire behavior considerations. H_0' greater than 1 indicates an overloaded tire and less than optimum off-road performance.</p> <p>d = average gradient to cone index of sand vs. depth in 0.5" layer at which vehicle will just be able to maintain headway in unaccelerated, level, straight-line operation.</p>			

... and for Tracked Vehicles

The situation with the soil mechanics of tracked vehicles is generally similar. Although the theoretical problem is simpler at the level of a first-order solution, it is nonetheless complex beyond this point. At the moment, precision of quantitative predictions of tracked vehicle performance in weak soils is low, particularly in critical situations where sinkage and slip are high and bellying incipient [Wheel Track, 1963].

Available first-order analytical methods for calculating the performance of tracked vehicles [Bekker, 1963; Evans, 1964; VMEA, 1965] show that, as with tires, simple nominal unit ground pressure (NUGP) overwhelmingly controls the basic level of performance of practical vehicles. Both Evans [1964] and WES (in their mobility index calculations for estimating tracked vehicle trafficability requirements [see VMEA, 1964]) include elements in their equations which reflect the less-than-ideal pressure distribution which occurs under a track, but in practice these have but small influence upon the calculations of ultimate go, no-go soil limits.

Micklethwait [1944] is generally credited with being among the first to point out that, due to track flexibility and the manner in which the vehicle weight is transferred to the tracks through the road wheels and suspension, actual pressures under a track may vary widely from the nominal or average pressure. Shortly after Micklethwait made his observation, tests, in which the behavior in soft soils of a standard vehicle was compared to that of the same vehicle fitted with a crudely girderized track, demonstrated the validity and potential importance

of this fact [Giles, 1945]. Later Bekker elaborated further upon the matter [1956] and numerous other investigators since have reconfirmed it in experimental investigations [cf. Uffelmann, 1955; Little, 1962; Freitag, 1965; Sofliyan and Maximenko, 1965].

However, acceptable mechanical means to provide effective track girderization when needed and still to allow the flexibility required at other times have not been forthcoming. In practice it is accordingly a question of a trade-off between maximum soft-ground performance and many other performance and mechanical problems. The result is that, despite their demonstrated disadvantages, flexible track structures have prevailed for all but slow speed machines. The feasible design choice has rather been between the use of a small number of large wheels, which are favorable from ride, obstacle-crossing and mechanical viewpoints, and a larger number of smaller wheels, to provide more nearly uniform track support, as successfully done on the WWII Weasel. The compromise of using large, overlapping wheels (such as was done on the German WWII Panther tank -- for other reasons) imposes both severe mechanical problems and performance difficulties in heavy soils which pack into the interleaved suspension elements, and is considered impractical. Perhaps some of the air-supported track ideas now under study [cf. PATA, 1966] may offer the long-awaited solution, at least for light vehicles. In the meantime, the situation is a textbook illustration of the compromises which must regularly be made in the design of any off-road vehicle.

Reece has recently pointed out that existing track (and wheel) analyses have been incomplete in ignoring the development of what he has termed "slip sinkage" [1964, 1965, 1966]. To be realistic, calculations of sinkage, and hence of motion resistance, must allow for the fact that at high tractive loads the supporting capacity of the soil under the vehicle is seriously reduced by the simultaneously applied tractive shear [see also Yong and Osler, 1966]. In addition, as in the case with wheels, there has thus far been no serious treatment of the track problem including soil dynamic reactions or other aspects of the complete soil-vehicle dynamic picture. Finally, again as for wheels, the soil mechanics of tracks is fragmented by lack of an accepted, validated soil value system.

Vehicle-Soil Mechanics -- Directions for the Future

As the master link in the chain of terrain-vehicle relationships needed to permit the valid application of systems approaches, and particularly in relation to these needs, much remains to be done in vehicle-soil mechanics. Knight and Freitag [1964] have properly suggested that future research must be more objective than that of the past. This is primarily the responsibility of those working in the field, but they would be greatly aided by more serious efforts, direct and indirect, to validate their theoretical and laboratory findings by careful field test work.

And it is still not too late to undertake the careful, painstaking, uncommitted dimensional research which would realign the foundations of

the entire vehicle soil mechanics structure. A properly designed program could go a long way toward establishing the single accepted soil value system which has thus far proven so elusive, and beginning study of the practical aspects of soil-vehicle dynamics.

Young has recently called the attention of soil-vehicle workers to a powerful method to handle the "distortions" which must occur in attempting to work with models in real soils having both cohesion and friction [1965, 1966]. This problem was recognized from the beginning of soil-vehicle model considerations by Markwick [1944]. It has bedeviled much of the work since [of. Liston and Hegedus, 1964; Hegedus, 1965; Goodman et al., 1966; Goodman and Hegedus, 1966; Wills, 1967; Reaves, 1966] and led to a needlessly gloomy outlook on the possibilities for the use of scale-modeling as a practical design tool (rather than a tool for theoretical work). Others, of course, have been more sanguine and have proceeded accordingly [of. Nuttall, 1949; McEwen and Willetts, 1955; Nuttall and McGowan, 1961; Schuring, 1964, 1966; Schuring and Erori, 1964; Erori and Schuring, 1965, 1966].

The distortions involved in practical vehicle-soil scale-model work are outlined in Table II, taken from Nuttall and Raymond [1956]. This table also illustrates some of the possibilities for exploratory experimental study of vehicle-soil dynamic relationships which the dimensional approach opens.

As another basis for further progress, the recent suggestions of Reece bear most careful consideration [1965]. He has proposed that the vehicle soil mechanics problem be treated within

TABLE II
 SCALING OF DYNAMIC MODEL-SOIL SYSTEM FOR GEOMETRIC SCALE MODELS^{1,2}
¹ λ = linear scale ratio between model and prototype = L_M/L_P
 From: Nettell, Reissner 1956

Case No.	I	II	III	IV	V	VI
TYPES OF SOIL REACTION OF PRIMARY IMPORTANCE TO SYSTEM BEHAVIOR						
Cohesive shear	X	X	X	X	X	X
Frictional shear	X	X	X	X	X	X
Body	X	X	X	X	X	X
Inertia	X	X	X	X	X	X
Viscous (visco-plastic and/or elastic)	X	X	X	X	X	X
POSSIBLE SCALING OF SOIL PROPERTIES INDICATED						
Cohesion, c (PL ⁻¹)	1	1	1	1	1	1
Angle of internal friction, ϕ (1)	1	1	1	1	1	1
Specific weight, γ (PL ⁻³)	1	1	1	1	1	1
Plastic viscosity, μ (LY ⁻¹)	1	1	1	1	1	1
Elastic viscosity, η (LY ⁻¹)	1	1	1	1	1	1
Modulus of elasticity, E (PL ⁻¹)	1	1	1	1	1	1
Shear deformation parameter, β (1)	1	1	1	1	1	1
CORRESPONDING SCALING OF SYSTEM INDEPENDENT VARIABLES ³						
Loads, W (P)	1	1	1	1	1	1
Speeds, V (LY ⁻¹)	1	1	1	1	1	1

Notes: Geometric similarity applies to soil and vehicle alike as required by problems.
¹ λ includes soil grain size and stratification, etc., and vehicle weight and mass distribution as necessary.
² Gravity constant, " g ", is considered fixed.
³ Extends to all important manifestations of each property in complete soil system behavior, including changes under vehicle action.
⁴ Extends to all important manifestations of each variable in complete model behavior.
⁵ Denotes scheme for each case probably most free local in present state of knowledge.

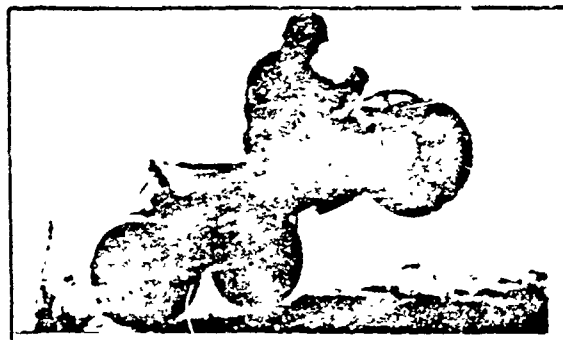
the framework of engineering soil mechanics insofar as possible, introducing dimensionless semiempiric elements only as necessary to deal with such things as unconsolidated soils, extreme stratification, dynamic properties, etc., which are peculiarly of interest in soil-vehicle work. Implicit in his proposal is a return to the accepted soil value system of civil engineering soil mechanics and to dimensionally sound basic equations. In that respect, Reece's proposal is not new, of course. The several systems extant each started out in one degree or another to do just this.

While these technical objectives are important, the problem of motivation is probably even more so. Workers in vehicle soil mechanics are handicapped by a long-standing and continuing lack of responsibility for the correctness of their work. Until recently, there has been no use or demand for greater precision than provided by the approximate methods they have developed. There has been no feedback from practical design success or failure that could be directly related to the adequacy or inadequacy of their vehicle-soil models. Accordingly, every man's answer has been as good as the next's, and correctness or adequacy has tended to be judged by the number of integral signs in published papers. The blame for this situation is shared in many places. However, a solution which could benefit the entire vehicle design and R&D process appears to lie within the organizational framework which governs the conduct of military vehicle design.

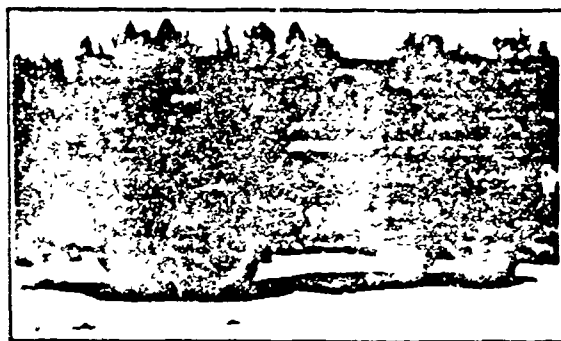
WHEELS



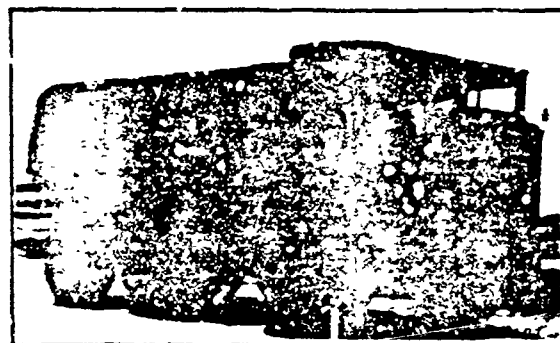
Rolling Corp. 1944



ENAG 1940

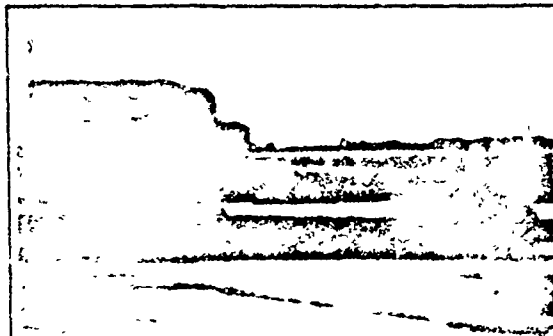


(8T Goer. AM520E1, 1964)

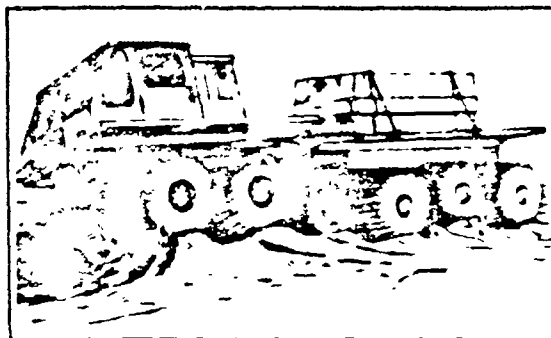


(5T, T51E1, 1951)

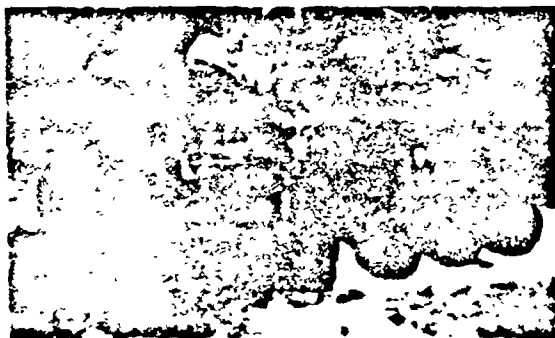
WHEELS



(FWD, 195c)



(VMEA, 1964) . .



(Lockheed, 1964).

Other Aspects of Terrain-Vehicle Technology

. . . Roughness

The dynamic behavior of a vehicle operating on a strong, hard surface of known geometry can be calculated to a high precision by the methods of engineering mechanics. The elements of the problem are the geometry of the surface and of the vehicle, the mass of the vehicle and its distribution, the articulation of its parts, the elastic and damping characteristics of its structure and running gear, and the coefficients of traction of its running gear on elements of the surface. Complexity of vehicle geometry and often of surface geometry makes this a problem for computer solution, but the fundamental equations are known and need no particular research. The accuracy of the results depends entirely upon the detail with which the vehicle-surface system is modeled and the accuracy with which various dynamic constants are assigned [Smith, 1965].

While the behavior of any given vehicle operating at a given speed on a given stretch of hard surface is fully determinate, the problem of surface roughness and its effect upon vehicle "ride" lends itself rather to statistical treatment. This approach has been under study for some ten years, primarily by Cote, Kozin, and Rogdanoff, who are currently summarizing their work in the *Journal of Terramechanics* [four parts, starting with Vol. 2, No. 2, 1965; see also Holland et al., 1965]. It is an important extension of related studies in automobile engineering, communications, seakeeping, and road and airfield work.

For purposes of statistical treatment, the surface is considered to be a weakly stationary random process and may be specifiable, accordingly, in power spectral density (PSD) terms. The PSD then becomes a relatively simple descriptor of what is in practice a highly complex surface. The power of the PSD approach is that, within a range where the vehicle vibratory system may reasonably be considered linear, the vibrational motions, accelerations, etc., of a vehicle operating on the surface are relatively simple vehicle dependent functions of vehicle speed and of the PSD of the surface.

Other work has demonstrated that human responses to continuous random vibration may also be quantifiable as relatively simple functions of the PSD of various elements and components of those vibrations [Hanamoto, 1964]. Since it is predicated in terrain-vehicle studies that speed of an off-road vehicle in moderately rough terrain is limited primarily by the tolerances and judgments of the driver, the PSD approach to describing terrain roughness has a relatively short and direct linkage to off-road speed. Van Dusen has suggested that the linkage may, for design purposes, be shortened still further by considering the vibration characteristics of the vehicle when subject to a "white noise" input (which is an input having a constant power over a wide range of frequencies) rather than the actual terrain PSD, and relating vehicle response to human response in three critical frequency ranges [1965].

There is presently considerable concern to establish precise human comfort, tolerance and/or related judgment criteria. Approaches range from the use of simple acceleration limits [Aspinwall and

Oliver, 1964; Mathews, 1964; Rotenberg and Burchachenko, 1966] through various detailed factorings of the total vibration environment into PSD's of various components [Nanamoto, 1964; Van Dusen, 1965], to an overall "absorbed power" concept recently proposed by Pradko et al. [1955, 1965], which employs PSD's of the vibrational environment directly. Incidentally, Berliet, the French designer of large off-road trucks in use in the Sahara considers that the longitudinal vibrations of the driver are most discriminating [1964], whereas most of the work in this country has been concerned largely with vertical motions and accelerations. Any criterion, however, is going to be statistical in nature and variable to some extent with the physique, condition, and élan of the driver, so that the practical usefulness of developing high precision in this area appears limited.

In summary, means exist to characterize a given stretch of terrain of complex roughness in relatively simple terms, although the field and analytical methods are quite complex. Means to convert this type of information into actual vehicle behavior at any speed exist at all levels of precision. And finally, reasonable measures of the human tolerance limits which will ultimately control operating speeds have been developed. From the viewpoint of design calculation, the system appears adequate and complete. Lacking are the orders of magnitude of PSD's which may reasonably be expected in terrains of various kinds. Accordingly, such further work in this sector of the terrain-vehicle relationship problem as is needed is largely in the area of environmental research, to classify terrain in meaningful terms and to establish PSD ranges associated with each.

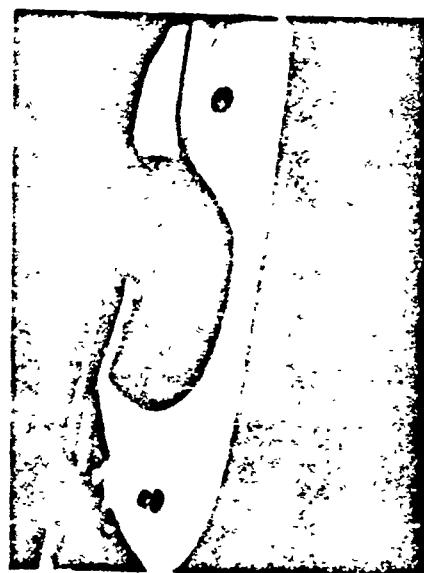
WHEELS



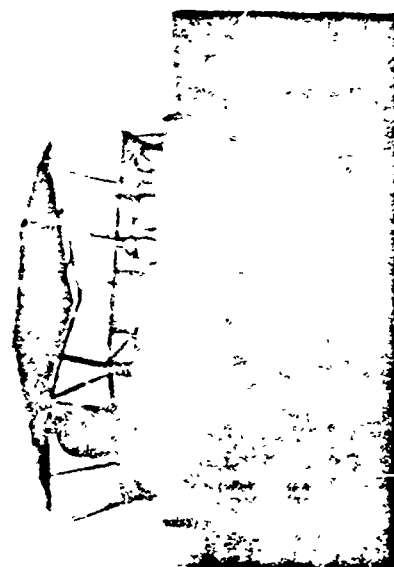
BIG (BAHC, 1950)



SOFT (Gulf, 1938)

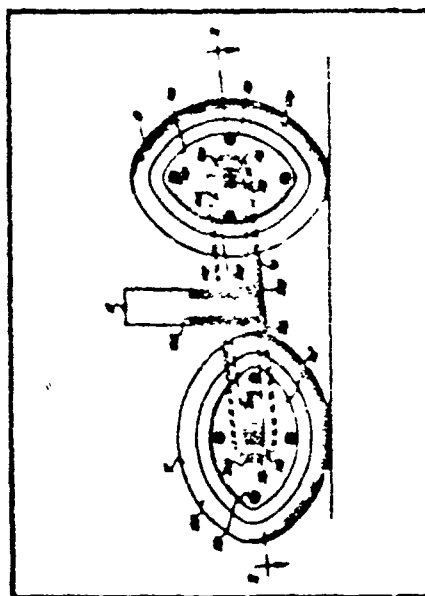


LITTLE (Penguin, 1964)

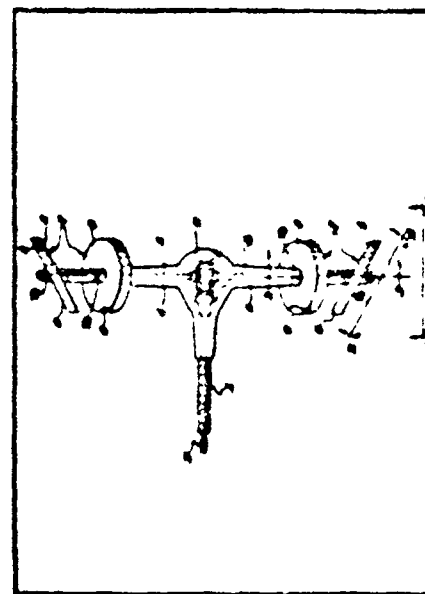


HARD (Ceramic, 1952)

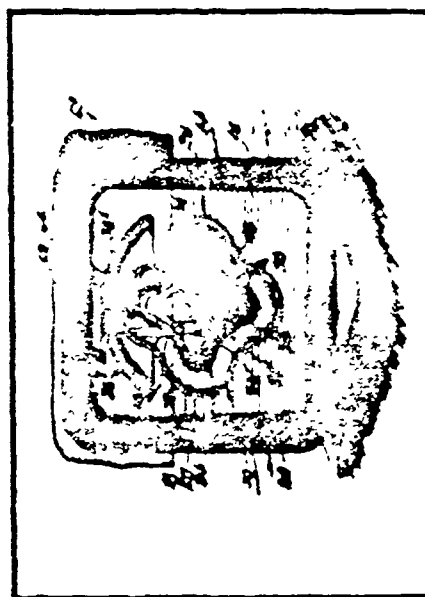
WHEELS



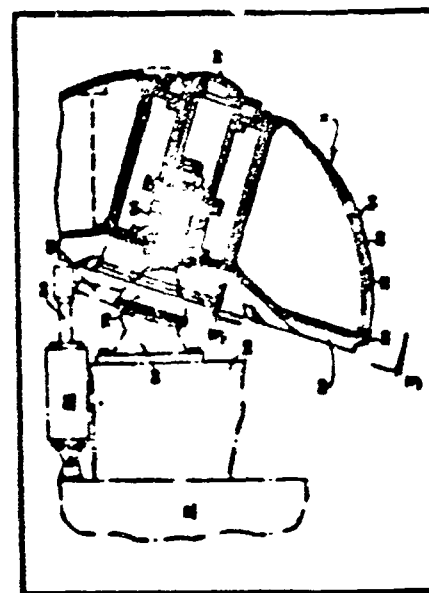
OBLATE (Kopczynski, 1950)



TILTED (Kopczynski, 1954)

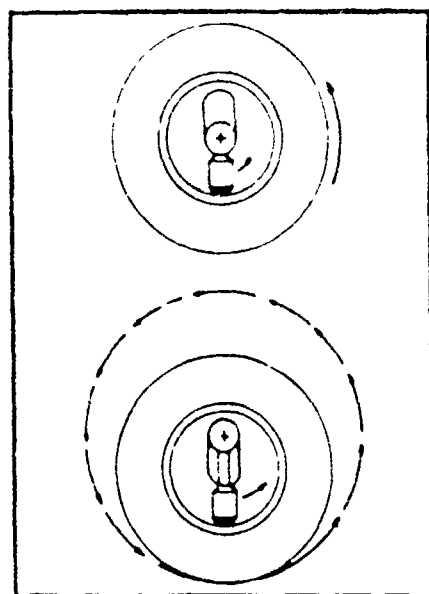


SQUARE (Streda, 1954)

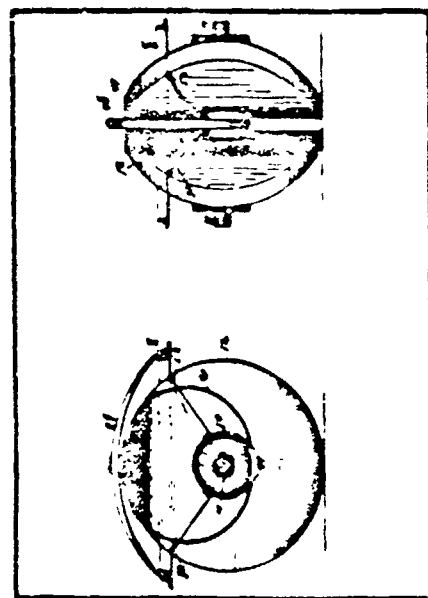


HEMISPHERICAL (Aghnides, 1961)

WHEELS



ECCENTRIC (Dunlop, 1954)



WARPED (Beskow, 1907)



ROUND (Alvis Stalwart, 1964)



DEFORMED (Markow, 19)

and even

While the terrain roughness problem is usually discussed, as above, in terms of human tolerances, it also has profound and perhaps even more important use to the designer in establishing the fatigue stress environment within which the vehicle as a whole or any of its components must survive. Suspension components, of course, are most sensitive to variations in speed and accordingly their detailed design can benefit most from this type of terrain quantification [cf. Blythe, 1965]. Note however, that even here the human component is important. Rational design should obviously be based upon realistic estimates of operating speed in terrains of varying severity, and these in turn are a matter for the tolerance and judgment of the driver, who responds to the behavior of the complete vehicle as he senses it at the driver's seat and controls.

. . . Obstacles

These geometric features of the surface which are too large in relation to the size and perhaps the speed of a vehicle to be included reasonably in the statistical description of the terrain must be treated, both by the driver of the vehicle and by the analyst, one at a time, as obstacles. These include such things as boulders and stumps, along with more continuous features such as drainage ditches, minor scarps, etc. The problem is both qualitatively and quantitatively well understood. While in marginal cases some vehicle dynamics are involved, simple static analyses such as first offered for conventional wheeled vehicles by Rettig and Bekker [1958] will often suffice from

a design viewpoint to establish the first order go, no-go aspects of the vehicle-terrain relationship. Similar generalized static studies on the obstacle climbing abilities of articulated wheeled vehicles and of skid-steered tracked machines have recently been published by Jindra [1966] and Janosi [1966], respectively. The dynamic aspects, such as dramatically investigated by Smith [1965] in the course of demonstrating the validity of an overall vehicle-terrain dynamic model, are, however, potentially valuable in establishing maximum stress levels for which components must be designed.

Basic vehicle indices of the potential to deal with obstacles on firm surfaces are such simple things as angles of approach, departure, and break, ground clearance, suspension compliance, dynamic clearances, etc. Current work at WES with yielding obstacles [cf. Cohron and Werner, 1964] brings into the problem such additional considerations as the traction available to a vehicle and the strength of the materials which compose the obstacle. While some rough values for estimating the magnitude of effects of this sort should be available to the vehicle designer, detailed elaboration would not appear profitable.

The same may be said for considerations of speed of operation in fields of obstacles such as forests. WES work [Cohron and Werner, 1964] has demonstrated that under idealized conditions the maximum feasible speed of a given vehicle (with a given driver) is a relatively simple function of the mean spacing of the trees in relation to the size of the vehicle. In practical situations, however, such factors as visibility in relation to spotting obstacles and maintaining a desired

course will usually alter this basic relationship beyond recognition. Accordingly, highly detailed exposés of this kind of action can be of only little practical use to the vehicle designer. Other aspects of vegetation *per se*, such as their indirect influence upon traction and/or visibility would seem to fall in the same category.

Past Uses of Terrain-Vehicle Technology in Design

The direct uses to which current terrain-vehicle technology have been put are quite limited. Such things as nominal unit ground pressure, angles of approach and departure, ground clearances, etc., have been of concern to off-road vehicle designers for many, many years (*cf.* TM 9-2800, 1943). Insofar as terrain-vehicle research, and more especially vehicle soil mechanics research, has improved general understanding, it has been of some value. However, the period of the research has also been a period of increasing awareness of off-road mobility problems generally, so that the net effect of the research *per se* in this regard may actually be negligible.

Prof. W. P. Buchele (Univ. of Iowa) has suggested that one reason for the slow spread of more refined methods and concepts may be that "the designer tends to use what he learned in school" (1954). Perhaps still more basic is the fact that the terrain-vehicle research has demonstrated that the performance of a vehicle off-road is overwhelmingly determined by its form and scale in relation to nature and is but little influenced by overall minor details and gadgets.

For the research results have emphasized again and again that no major gains can be made in the off-road mobility of ground-crawling machines without major changes in overall vehicle form or configuration. There is no cheap way. There are no gimmicks which will endow a standard 6x6 truck with the modest soft-soil performance of an M113 APC.

The basic level of mobility of a new vehicle is accordingly fixed very early in its design, frequently, in the military case, in the detailed statement of "requirements" before "the designer" puts a line on paper [cf. Tuttle, 1964]. The designer -- in this case the engineers and draftsmen seeking to meet the requirements in a piece of working hardware -- understandably has little practical interest in the broad generalized results of the terrain-vehicle research to date, which relate largely to the form and fundamental outlines of the design. Scope for the designer's efforts is largely limited to getting the last few percent of performance within the tight and sometimes unreasonable limits which have been handed him. The research to date simply has not dealt with this level of detail, where fundamental considerations show there is no scope for significant improvements.

Such use as has been made to date of terrain-vehicle research, and of vehicle soil mechanics in particular, has been in a few, relatively recent design and concept studies for the military. These studies are an important early step in the overall process by which new vehicles are eventually produced, and are one appropriate place for terrain-vehicle inputs to the design process. AFAC has demonstrated use of the LLL system in such studies

[Harrison et al., 1959] and in generalized operational studies [Lucas, 1961]. They also now regularly use this method to compute the soil performance of proposed new vehicles for comparison with existing vehicles of known performance [of. Moore, 1965; Arne and Bischoff, 1961]. In much the same manner, the British FVRDE is reported by F. L. Uffelmann (1964) to make some limited use of Evans' tracked vehicle equations.

Chrysler has employed the LLL calculation procedures in several concept studies of tactical trucks [of. Jones and Lett, 1963; Lett, 1965], one of which led to the development of the XM410E1 2-1/2-ton 8x8 [Moore, 1965]. Dugoff et al. used a broad base of vehicle soil mechanics indices, similar to those developed in Appendix III, in a study of "coupled-mobility-devices" [1964]. A recent published example of the use of soft-soil performance calculation procedures (both LLL and WES) was in "Vicksburg Mobility Exercise A" [VMEA, 1965], in which a beginning was made at studying the trade-offs possible between inherent vehicle off-road capability and various modest levels of engineering support effort. Rymiszewski has recently utilized a computer to develop curves showing tires and tire combinations expected to produce equivalent performance in soils according to current LLL theory [1966]. These should find wide use in future design studies.

The ARPA/Buships/Chrysler Marsh Screw is considered by B. D. Jones of Chrysler to have been generated in relatively free response to a functionally stated operational need and associated environmental information, although none of the terrain-vehicle calculation procedures under

discussion were specifically employed. Jones points out that, by and large, use of environmental information in the design of general purpose vehicles has until now been largely "intuitive" (1964).

On a far more modest level, as noted earlier, AIAC from time to time has used a simple MUGP specification in outlining the objectives of various design studies of both wheeled and tracked vehicles; and Buships, in designing their wheeled amphibians, makes use of the Eklund tire load inflation schedules for selecting tires.

Meanwhile, back at the moon, NASA has accepted the LLL system as a basis for designing and evaluating potential moon vehicles [Wong and Galan, 1966]. In surprising contrast, it is reported that although General Motors received the prime U. S. contract for work on the Main Battle Tank for the 1970's (being developed by the U. S. Army in cooperation with the Army of the Federal Republic of Germany) [Army, May 1965; Ordnance, May-June, 1965], they have not utilized their in-house capability at the Defense Research Laboratories in this effort.

Finally, in relation to commercial vehicles, there has been almost no use of formal terrain-vehicle methods. The known exceptions are such use as Roger Camuant made of the LLL methods and concepts in the process of designing his pacesetter Gama Goat [Journal of Terra Mechanics, Vol. 1, No. 1, 1964] (ultimately for sale to the military); Kerr's long use of the Eklund formulas in selecting tires for equipment for the Arabian American Oil Company [ARAMCO, 1953] for use in Arabia [Kerr, 1950, 1953, 1956]; the

crude loading and scaling concepts which guided the design of the muskeg-going Musk-Ox for Imperial Oil [Thomson, 1961]; and some trafficability studies made during the development, under the aegis of Canadian pulpwood industry, of the current successful line of mechanized pulpwood transport machines [Boyd, 1962].

There is clear recognition of the need for terrain-vehicle understanding and sound, organized terrain data in the timber and pulpwood industries, as evidenced by numerous papers on the subject presented at a meeting of the International Union of Forest Research Organizations (Section 32: Operational Efficiency) in Montreal in 1964. While it is discouraging to see that this commercially oriented group appears to be largely unaware of the status of pertinent work already underway, it is consoling to see that their independently conceived approach closely resembles that already undertaken [Stromnes, 1964; Putkisto, 1964].

CURRENT MILITARY VEHICLES

Despite the hue and cry, there have been measurable improvements in the off-road mobility of many of our military vehicles over the past 25 years. Moreover, these have usually been accompanied by significant improvements in rough terrain speed, durability, reliability, and perhaps maintainability, and in overall logistic economy. The current generation of tactical trucks* with which the Army is now considering reequipping itself [Sisson, 1965] in fact represents a considerable advance over the standard equipment it might replace. All are swimmers. Cross-country speeds in rough terrain have been roughly doubled, overall dimensions reduced, cargo areas increased, and lubrication operations reduced [Moore, 1965].

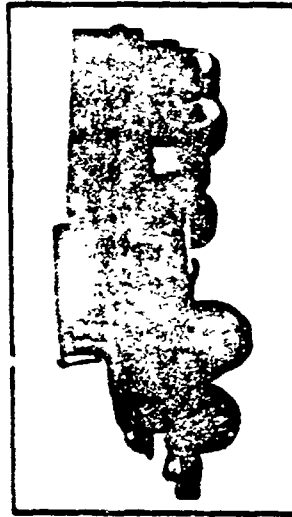
The appearance of stasis is due to three factors. First, the Army, in the past at least, has limited itself for sound financial and logistic reasons to reequipping itself with ground vehicles (including tank weapons systems) upon a cycle of approximately ten years. Second, and for not so sound reasons, the peacetime development cycle for military vehicles from the first gleam of a requirement to the time when vehicles purporting to meet it reach the field is approximately six years, and has been as much as ten or more. And third, the soft-ground mobility of various classes of standard tracked vehicles has indeed not materially changed.

Wheeled Vehicles

The soft-soil performance indices developed in Appendix III and summarized in Table I of the preceding section were used (in their original

*XM561 1-1/4-ton 6x6, XM41021 2-1/2-ton 8x8, and XM656 5-ton 8x8 [AMC TIR CD-10, Supp. II, 1963].

Std. 2-1/2 T Cargo Trucks



NWII

2-1/2 T 6x6



1950 65

M35

PROGRESS

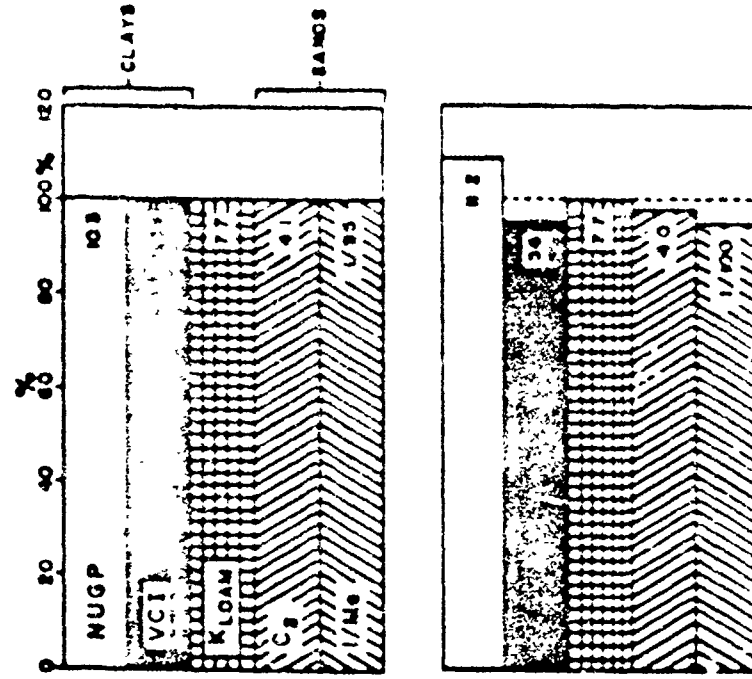
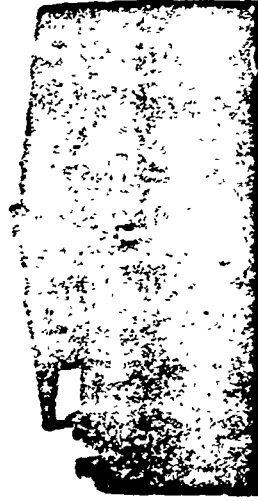


Fig 1 (Continued)

Std. 2-1/2 T Cargo Trucks

PROGRESS



1966-?

XM110E1



???

VNEA

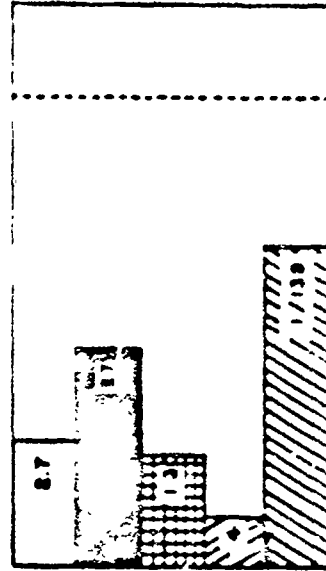
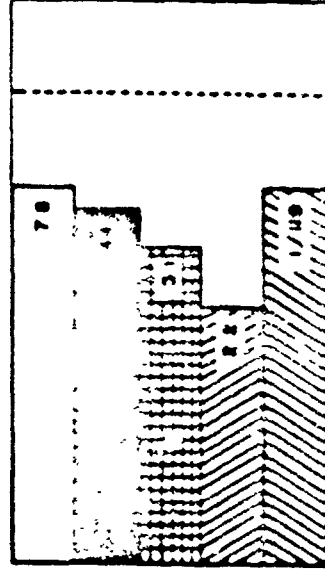


Fig 1 (Concluded)

form where possible) to evaluate the soft soil mobility of the standard tactical truck family of WWII, that of the 1950-1963 period, and the new family which is now coming into being. The results are summarized in Table III, and are typified by the graphic presentation of the results for 2-1/2-ton trucks shown in Figure 1. The table and figure also include calculated indices for a group of vehicles existing (or nearing existence) which have still greater soft ground mobility, and which demonstrate how much more soft ground performance potential might even now be built into working machines on tires.

From the table and figure, it is clear that there has been steady progress in improving the soft ground mobility of this type of vehicle since WWII, and that the available new family represents a significant improvement "to a degree not recognized by a public almost stupefied by the dazzling feats of aeronauts, astronauts, and aquanauts" [Watson, 1966]. It is also clear that at least one more major step in this direction could already be taken.

It is instructive to consider these results in the light of the curves of cumulative worldwide frequency of Rating Cone Indices developed by WES from analyses of their extensive data on temperate and tropic soils, and shown in Figure 2 [VHEA, 1965]. While these curves represent a very preliminary picture, there is no question but what any more complete presentation would have similar characteristics.

Considering the WWII 2-1/2-ton truck (VCI = 59) in relation to these curves, it develops that on a worldwide basis approximately 18 percent of

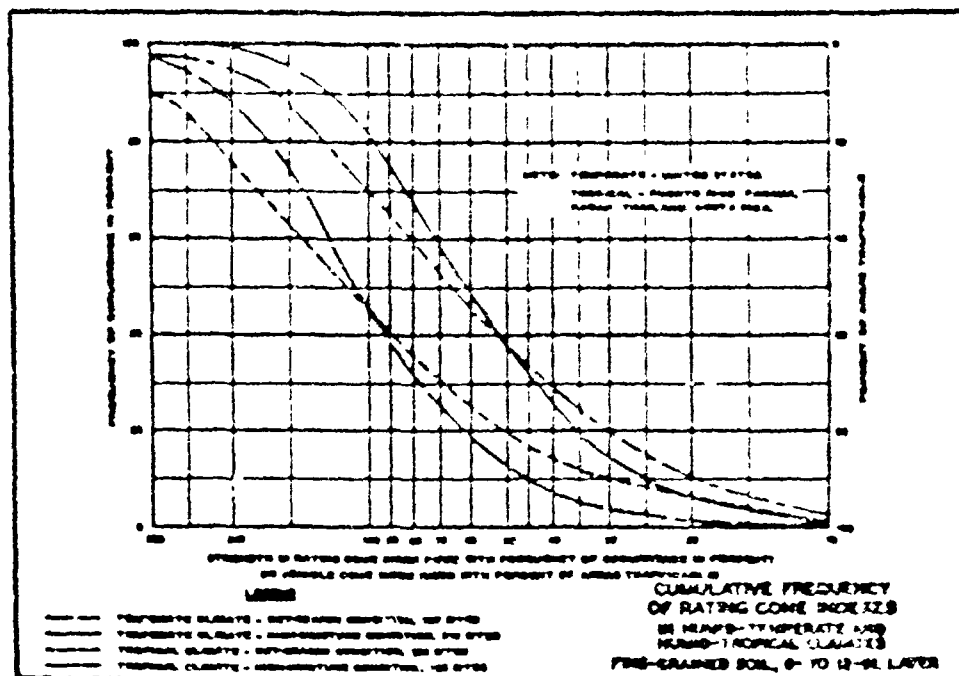


Fig. 2

TABLE III

SOFT-GROUND MOBILITY INDICES FOR WHEELED TACTICAL VEHICLES

(All vehicles with single tires except *)

Calculated from original equations (see Appendix III).

		Floater	YCI _{eq}	YCI _i	r_{base}	W_0	K_{base}	C_{clay}
World War II								
Jeep	4x4		47	30	5.2	80	5.6	3.3
3/4 T	4x4		50	34	5.0	97	5.6	3.8
2-1/2 T*	6x6		50	34	3.9	91	5.6	3.9
4 T	6x6		64	41	3.7	99	5.6	4.7
1950-1965								
M18	1/4 T 4x4		41	26	3.3	100	2.7	2.2
M17	3/4 T 4x4		53	35	4.4	97	3.5	4.2
M34	2-1/2 T 6x6		62	37	3.9	102	3.4	4.6
M41	5 T 6x6		3	46	4.3	94	4.1	5.7
1966-7								
M111	1/4 T 4x4		41	24	3.6	100	2.4	2.7
XM541	1-1/4 T 6x6	F	43	22	2.2	122	1.9	2.5
XM410R1	2-1/2 T 6x6	F	30	26	2.6	121	2.4	3.1
XM54	5 T 6x6	F	56	26	2.1	126	2.2	3.0
XM510R1	8 T 4x4	F	93	69	3.2	130	3.5	8.8
Camel Coast								
VMMA	1 T 6x6	F	30	18	2.0	126	1.6	2.8
	2-1/2 T							
	10x10	F	38	11	0.5	144	0.3	1.0
Gulf Buggy	3/4 T 4x4	F	12	5	0.2	148	0.2	0.5
Power Wagon								
w/Terra-Tires	3/4 T 4x4		34	15	1.0	156	0.9	1.6

temperate wet season conditions, 24 percent of tropic wet season conditions, and some 43 percent of tropic and temperate high moisture conditions in level, fine-grained soils would be untrafficable to this vehicle. In comparison, the corresponding figures for the new XM410F1 2-1/2-ton 8x8 (VCI = 44) would be 10 percent, 16 percent, and 32 percent, respectively. By whatever measure, the areas untrafficable to the newer vehicle are reduced by 30 percent or more.* Further, the VMEA 10x10 concept machine would find that, as compared to the WWII vehicles, areas untrafficable to it were only one-third as extensive.

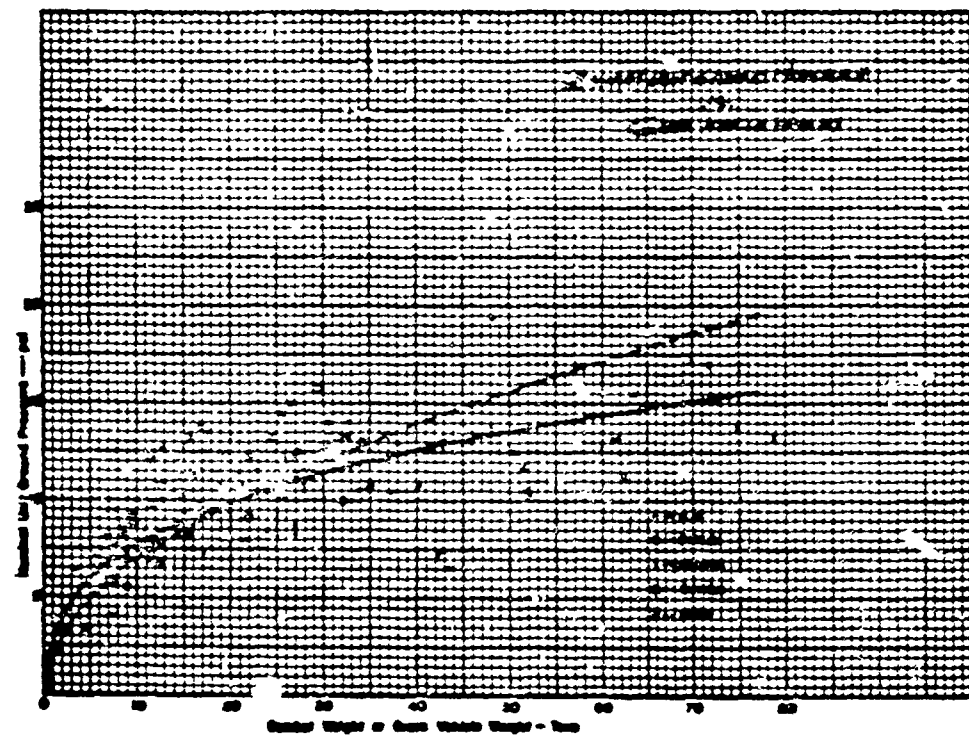
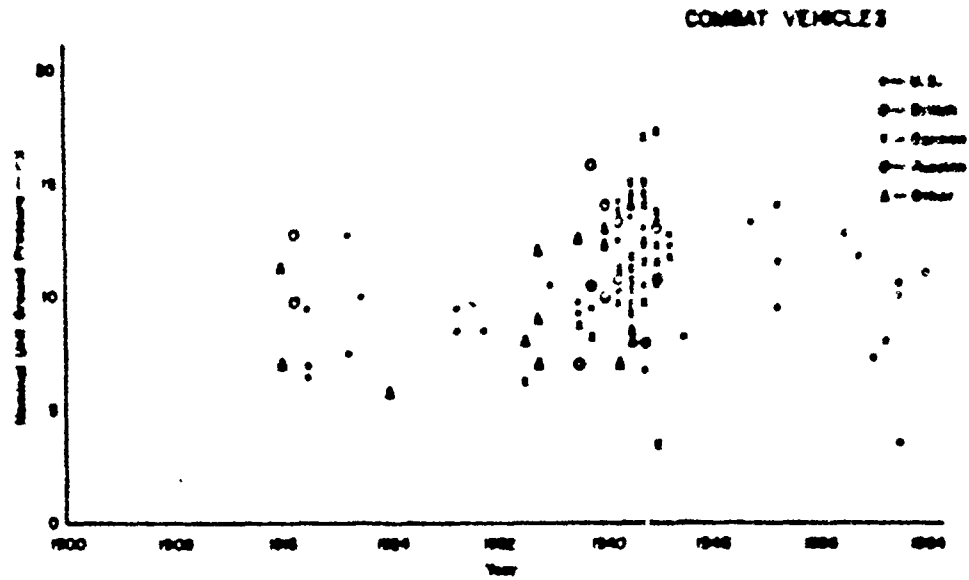
In contrast to the rest of the new family, the 8-ton GOER 4x4 (XM521E1) comes off badly (see Table III). The original concept of the GOER's was that they should be extra high mobility vehicles with performance to match that of tanks. This was to be achieved by the use of the articulated four-wheel layout of commercial earthmoving scrapers, with large diameter, low pressure tires, all-wheel drive, high power-to-weight ratio, and lightweight design [Johnson et al., 1959; AMC TIR 30.3.1.3, 1964; Harshfield, 1965]. In part because of its having gone over its design target curb weight by some 55 percent (and hence over the designed gross weight by nearly 30 percent), the power-to-weight ratio of the 8-ton GOER is marginal and all fine-grained soil mobility indices indicate that its soft soil performance will not match that of current main battle tanks (see Table V), and that

*As this report is finally frozen--Aug 66--there are signs that the XM410E1 may be a dead duck, regardless of its performance potential [Jones, 1966; Automotive Industries, 1 July 1966].

it will be denied access to approximately the same proportion of the world's level terrain as was the WWII family of tactical cargo trucks. Moreover, in comparison to the rest of the new truck family, the tires of the 8-ton GOER are somewhat overloaded even in sandy soils.

Of course, the simple soft soil mobility indices calculated do not tell the whole story of off-road mobility or even of soft-ground mobility. The large actual tire diameter and corresponding high ground clearance of the GOER-type of machine will permit it to operate successfully in deep mud underlain at reasonable depth by a hardpan, where some of the other wheeled vehicles might have difficulty. Also its use of frame articulation for steering and to insure good conformance to major ground irregularities is a mobility advantage which cannot be quantified at this time. On the other hand, the 8-ton GOER is unsprung, so that the overall picture can hardly be considered one of progress from a ground mobility viewpoint.

Although the general situation with tactical vehicles on tires is one of advance insofar as mobility is concerned, within the last several years there has concurrently been considerable lost motion in various attempts to build (on both wheels and tracks) tiny, gimmicky "toys," to give every infantryman his very own pair of powered roller skates [cf. Harrison and DeStefano, 1962; Bischoff, 1964; Fuller, 1964; Umberger, 1966]. These attempts have necessarily ignored the scale of nature. A very small machine gives all of the leverage to nature and literally makes mountains out of molehills. In addition, these efforts have generally been pursued in the fallacious belief that because the vehicles are small they could be, even



b.

Fig. 3

must be, cheap and simple. Quite the reverse is in fact true. The concept of a cheap and simple ground-crawling, toy magic carpet is doomed to failure and always will be. There is some evidence that the harsh experiences of Vietnam may be, temporarily at least, lessening enthusiasm for such a gadget approach ("Fashions in War," *Newsweek*, 27 Dec 1965).

Tracked Vehicles

In contrast to the improved soft-ground mobility of the new tactical trucks, the basic soft-ground mobility of various classes of tracked military vehicles has indeed remained largely unchanged for a number of years. Despite having achieved new levels of durability and reliability and considerable increases in fire power, the mobility component of tank weapons systems, for example, has remained relatively constant. Their nominal unit ground pressures have stayed in the same range for nearly 40 years (Fig. 3), and the basic form of the tank has been frozen for some 25 years [cf. Ordnance School, 1958; TM 9-2800, 1943, 1947, 1953; TM 9-500, 1962].

Early experience with the first WWI tanks was epitomized by Crompton in a recommendation that their gross weight should be limited to about 30 tons and their nominal unit ground pressure to about 9 psi [Legros, 1921]. Some 35 years later, Uffelmanna and Evans concluded their post-WWII (1953) study of tank operation in the North European plains by recommending that the gross weight of tanks for use in that general area be limited to approximately 35 tons and their nominal

unit ground pressure to 8 psi [1965]. While these recommendations have been heard [cf. Ciesra, 1963; Butterfield, 1966], neither appears to have been heeded, except perhaps by the Russians [cf. Miller, 1966].

Some simple numbers bearing on tank performance are synopsized in Table IV, which shows gross weight, planform loading (see later), calculated VCI for 50 passes [VMEA, 1965] and for 1 pass [WNRE, 1965], horsepower per ton, and approximate speed in rough terrain for a small number of successful main battle tanks spanning a period of nearly 40 years. Exploitation of the vast increases in power made possible by advancing power plant technology, which has been capitalized upon in aircraft to increase their power and hence their speed by a full order of magnitude or more in the past 25 years, has been limited during the same period to an increase in tank horsepower-per-ton by a factor of only 2. Potential tank average cross-country speeds have perhaps quadrupled in nearly 50 years. The improvement which has been unofficially projected for the US/FRG Main Battle Tank for the 1970's (MBT-70) represents essentially a "brute force" approach, for the little published information indicates that the current mobility concept of that vehicle fundamentally differs but little from that of its immediate predecessors. In short, as of the moment, the cross-country mobility of today's tanks is "only marginally better than some tanks designed almost 30 years ago" [Ogerkiewicz, 1962].

Beginning late in WWII, the U. S. Army pioneered the development of armored personnel carriers (APC's) for infantry [Ogerkiewicz, 1965]. The current successful U. S. version, in worldwide

TABLE IV
MAIN BATTLE TANKS, 1917-1970(Y)

Year	Tank	Weight (T)	Platform Loading (psi)	MUGP (psi)	VCI ₅₀	VCI ₁	HP/T	Approx. rough terrain speed (mph)
1917 1919	British MK IV U.S. MK VIII	30 43	1.5 1.4	12.8 6.6*	63 41	44 26	4.1 7.7	3 } 3
1943	U.S. M4A4 German Panther Russian T34-85	36 50 34	2.7 2.9 2.4	13.2 12.5 10.8	84 70 61	46 44 39	21.3 13.9 14.5	5 } 5-16 10 } 10 }
1950	British Centurion X U.S. M48A2	37 52	3.2 2.5	13.1 11.7	77 63	46 41	11.1 15.8	10 } 10 10 }
1965	British Chieftain U.S. M60A1 German Leopard Russian T54/55	58 52 42 36	2.8 2.6 2.5 2.4	14.8 11.1 11.5 10.5	73 61 62 60	43 39 41 58	12.1 14.6 19.6 14.2	10 } 10-15 10 } 15 } 10 }
1970(Y)	US/FRG M6170	50(Y)	2.5(Y)	9.9(Y)	57(Y)	36(Y)	28.0(Y)	25(Y)

*L/T excessive - did not see service.

Ref: TM 9-2800, 1943, 1947, 1953
Ordnance School, 1958
Von Benger und Eiterlin, 1960
TM 9-500, 1962
Ogorhovich, 1962-1966
Engineer, 1 Nov 1963, 25 Oct 1963
Royal Armoured Corps Center, 1964
Engineer, 1965

Parker, 1965
Miller, 1966
Meyer, 1966



W113, 1959 Successful stud

use, is the M113, and its recent diesel twin, the M113A1 [Ogorzkiewicz, 1966]. Volume production has brought the cost of this tracked vehicle down to about \$1 per pound [Ogorzkiewicz, 1966], and long detailed development has resulted in high reliability and good durability. Moreover, the basic M113 track-laying chassis has been utilized for vehicles for missile carrying, command, and cargo functions [AMC TIR 33.7.2.1, 1964] which share its performance, reliability, and low cost [Quinn, 1965]. This basic family of vehicles has a gross weight of 10-13 tons, a nominal unit ground pressure of 7-8 psi, calculated VCI's of the order of 45, and has demonstrated generally good soft ground mobility both in tests [USATB, 1962] and field operations. The M113 has proved highly useful in Vietnam [Stafford, 1965; Battreel, 1966], although its mobility there still leaves something to be desired [cf. Moore, 1966], particularly in relation to crossing the omnipresent canals and drainage features [cf. *Congressional Record*, 5 Nov 1963]. In those areas of the world where the bulk of our current standard vehicle family is patently inadequate, the M113 family could be considered a viable stopgap [Moore, 1966].

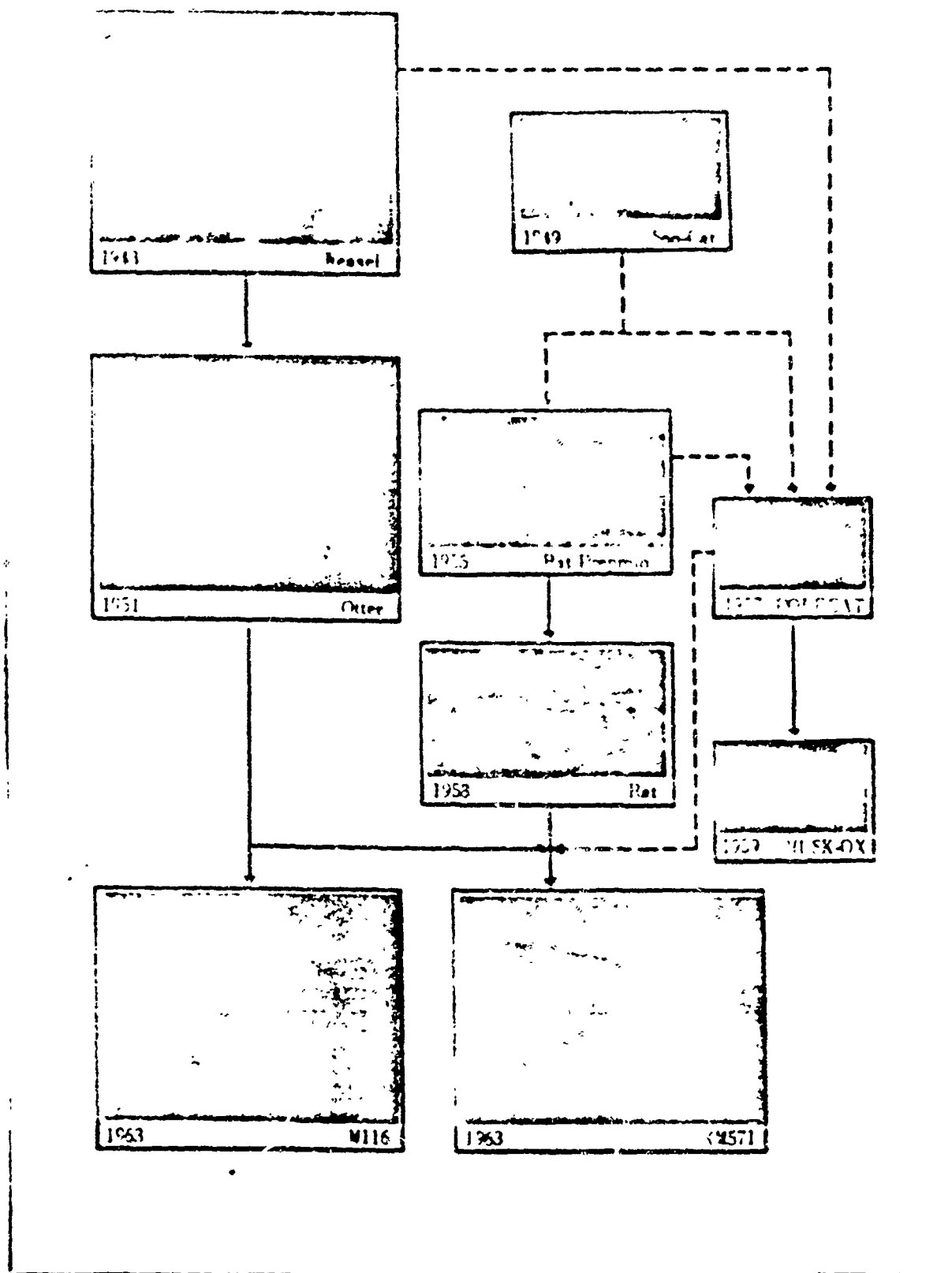
There is a third important class of U. S. military tracked vehicles which traces its immediate ancestry directly to the WWII Weasel [Churchill, 1945; Silverman, 1946; OSRD, 1946].^a Conceived essentially as snow vehicles, machines in this line of development are characterized by relatively low load-carrying capacity,

^aThe first small, self-propelled tracked vehicle designed specifically for snow operation appears to have been the Volsley motor-sleigh, used by Scott on his 1909 Antarctic expedition [Logan, 1918].

nominal unit ground pressures in the order of 1-3 psi, VCI's of the order of 10, and generally outstanding soft-soil mobility [cf. USATECOM, 1965]. This line has recently branched to the development of the first articulated tracked vehicle to be seriously considered for standardization by the U. S. Army, the XM571 1-ton carrier^a [AMC, TIR 12-5-1E1(1), 1963; *Defense Industry Bulletin*, March 1966]. The overall off-road performance of the XM571 has been found to be excellent [cf. USMC, 1965].

^aThe Swedish Army accepted the 1-1/4-ton payload articulated BV-200 for troop use in 1961 [Ogerkiewics, 1963].

SWR AND ARTICULATED VEHICLES



... Ve. Foreign Military Vehicles and
Commercial Vehicles

On the basis of various published reports [cf. Ogorikiewicz, 1962, 1963, 1965; Armer, Jan-Feb 1966; Engineer, 18 Sep 1964, 16 Apr 1965; Ordnance, Nov-Dec 1965; Miller, 1966; Meyer, 1966; Butterfield, 1966], our current tracked military vehicles, and particularly our main battle tanks, apparently have the same order of basic cross-country mobility as those of any foreign country, except perhaps the Russians, whose main battle tanks may have nominal unit ground pressures more nearly in the range 9-10 psi than the 11-12 psi range which characterizes our own [Miller, 1966]. Table V presents calculated vehicle cone index requirements for current medium and main battle tanks, based upon published information.

Our lighter tracked vehicles, if not superior, at least are generally equivalent to foreign military machines of the same class [cf. Ogorikiewicz, 1961, 1963, 1964; Baughman and Drinkard, 1962], while our new family of wheeled vehicles appears distinctly more mobile than anything apparently forthcoming from friend or foe [cf. Ogorikiewicz, 1961, 1963; Engineer, 18 Sep 1964; Dunn, 1964]. Once again, the exception may be some Russian equipment. Continuing Russian appreciation of central tire inflation control as a mobility feature [cf. Kozlov, 1956; Lavrentyev, 1958; Agikhin, 1960] and miscellaneous published work of vehicle-soil relations, off-road suspensions, etc. [cf. Krestovnikov, 1958; Tatarchuk, 1958; Lofarov, 1960; Eliseev, 1961; Bekas, 1963; Renov et al., 1962], suggests that their best wheeled vehicles may be very good. On the other hand, their hierarchy too may be largely unaware of the implications of the research results for which they have paid.

TABLE V

CALCULATED VEHICLE COME INDEX REQUIREMENTS
FOR CURRENT MEDIUM AND MAIN BATTLE TANKS¹

	GVW (T)	HP/T	MUW ²	YCI ₅₀ ³	YCI ₁ ³
U.S. M48A2	52	15.8	11.7	63	41
M50	51	14.7	10.9	60	39
M60A1	52	14.6	11.1	61	39
Russian T54/55	36	14.2	10.5	60	38
T10	50	13.8	9.0	56	33
German Leopard	42	19.6	11.5	62	41
British Chieftain	58	12.1	12.8	76	45
Vickers 37 T.	37	18.9	10.8	66	39
French AMX30	37	19.1	10.0	60	36
Swedish "5"	39	14.8	11.8	58	42
Swiss P261	40	11.5	12.9	76	45

¹Necessary parameters estimated from published information - see Table IV.
²YHEA, 1965.
³YHEA, 1965.

Our current military vehicles may also be compared to the best of those used in normal commercial off-road operations. Commercially produced vehicles for off-road operations fall into seven broad categories:

- 1) agricultural tractors
- 2) earthmoving equipment
- 3) mining and construction vehicles
- 4) vehicles for off-road transport
- 5) logging machines
- 6) vehicles for oil field and similar exploration work
- 7) sports vehicles

Except for the sports vehicles, the trend in all these commercial machines is toward bigger units operating on big tires, using diesel engine power, and increasingly with all-wheel drive. As yet there has been very little extensive use of exotic vehicles such as ground effect machines in the off-road working world. Thomson and Hemstock concluded in 1963 that such developments would not have a profound effect upon commercial off-road transport.

The only load-carrying commercial vehicles which are decidedly superior to even the best of our current family of military vehicles from an off-road mobility viewpoint, particularly in soft-ground conditions, are some of the essentially hand-built, low ground pressure, tracked machines used in oil exploration work. The showpiece vehicles are the Robin-Moore line, culminating in the RM200 12-ton carrier [Robin-Moore Mfg. Ltd., 1963], and the Mark-Ox 20-ton carrier [Mattall and Thomson, 1960], all first designed for operation

in the difficult summer muskeg conditions of Northern Canada. The latter two machines are particularly impressive. Both are articulated (on different schemes) and both have demonstrated the ability reliably to do big jobs in terrain conditions impossible to any comparable military machine. Both have been scrutinized by the military who, in their testing, bore out their high level of working mobility [USATB, 1962]. As of the moment, however, this is as far as the interest has gone.

Other successful low ground pressure tracked vehicles for the oil industry are more conventional, skid-steered, with wide tracks, narrow bellies, and relatively high track length to tread ratios ($L/T = 1.2$ is not unusual) [cf. Robin-Macdonell Mfg. Ltd.]. The Army and the Navy have bought a modest number of RM-110 and RM-75 vehicles for use in Alaska [Case, 1962] and Antarctica [USN, 1964, 1965], respectively, where they have in general performed creditably. As in the case of other low production, special purpose machines, however, these vehicles are designed insofar as practicable around commercial, off-the-shelf components, which has meant both that their curb weight was not as low as it might have been had optimized components been available, and that their ruggedness and reliability tended to fall short of military ideals. They were conceived, however, within a typical commercial design envelope which placed performance and economy at the top of the list of priorities and relaxed many other constraints upon the design wherever this proved necessary to achieve these goals. Together

with the larger articulated machines, they demonstrate clearly that when the job to be done can be specified, and where constraints are subordinate to functional requirements, the problems of off-road mobility can be solved in relatively straightforward, nonmonstrous ways.

New Running Gear Configurations

While all current successful off-road vehicles are mounted on tires or tracks of relatively conventional arrangement and mechanical details, a number of alternatives have been proposed in recent years, with varying degrees of success. By and large these alternative ground-crawling schemes are aimed at improving vehicle soft-ground crossing ability through the reduction of nominal unit ground pressures (NUGP), the reduction of peak pressures and/or (unwittingly or not) the provision of a new degree of variability in the ground contact mechanism better to match varying ground conditions. The basic configurations can often be broadly traced a long way back in off-road vehicle history, but new wrinkles have been added and advantage taken of new materials and technologies.

The most successful line of new development in off-road running gear to date has been the ultra-low pressure (1-3 psi) pneumatic roller concept pioneered by William Albee in the early 1930's with his "Rolligon" running gear and prototype vehicles exploiting it (Koville, 1954; Ford and Nilesen, 1954; Simonds, 1958). The concept has since branched to two lines. First, a continuation of the total Rolligon concept, including use of the bag as a roller, restrained between the vehicles and the ground as in a roller bearing (rather

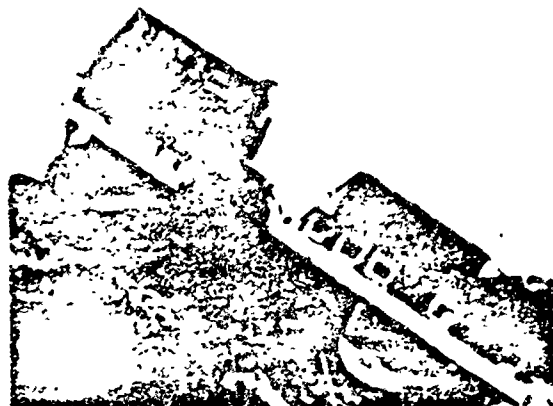
than as a wheel loaded through an axle), and drive by friction at the load-carrying contact of the bag with the drive/load support roller on the vehicle (rather than via axle torque). The total arrangement is exploited in a small number of frame-articulated nature 4x4 and 2x2 Rolligon vehicles built in recent years for commercial use (Rolligon Corp., Houston, Texas), and in the Airoil Truck which will be touched upon later.

The original Rolligon concept also triggered the successful commercial development by Goodyear of the Terra-Tire [cf. O'Avella, 1964; Goodyear, 1966]. The Terra-Tire is also an ultra-low pressure pneumatic bag, but, like a more conventional tire, carries the vehicle load through its axle, and is driven by torque applied to its axle. While Terra-Tires are now available in many sizes, they are generally wide in relation to their diameter, which is not considered desirable from a soil viewpoint [cf. Bekker, 1956]. However, these proportions permit fitting tires giving low MUCP's to more-or-less normally proportioned, normally laid out vehicles, and the performance gains from the lowered MUCP have in fact far outweighed any theoretical considerations [cf. Swamp Fox II, 1964]. Today, Terra-Tires are in successful use on vehicles ranging from such relatively normal machines as the 3/4-ton 4x4 Dodge Power Wagon to lightweight 4x4 marsh buggies which float on the Terra-Tires alone [cf. ARDCO, 1964].

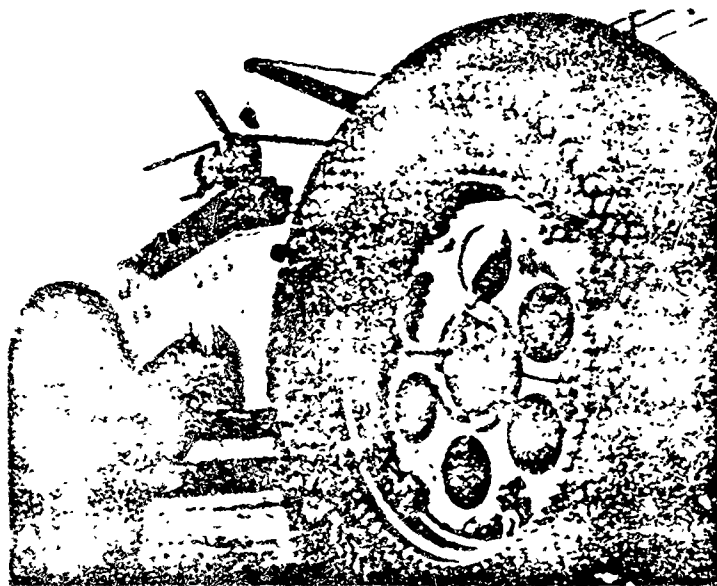
Until recently, tires of about 19-foot overall diameter were considered the practical maximum size (Gulf Marsh Buggy 128 x 33.5-66; SABC 34.00-41; LeTourneau 43-63) because of both manufacturing and shipping problems. However, the potential of

still larger tires, so much larger in some instances as to represent a qualitative change rather than a mere quantitative one, has continued to exercise the imagination. A. V. Roe, Canada, for example, proposed a while back a mobile oil-drilling platform for muskeg work -- conceptually similar to the barge-mounted offshore rigs now in wide use -- to be mounted on four 50-foot tires [Oil Week, 25 Sep 1961]. Preliminary trials at small scale of a new method of on-the-site tire construction, by weaving a large number of relatively manageable-size molded strips, have indicated that such tires could practically be built and shipped (in pieces) [Machine Design, 15 Aug 1965]. No immediate military usefulness for such large tires is apparent, however. The military tends to shun, where possible, putting so many eggs in a single basket.

Owing its present feasibility directly to the development of the Terra-Tire is the Airoll track-cum-wheel arrangement [Mrozok, 1962]. This is a chain of free-rolling pneumatic rollers circulating around a fixed ponton through which they are loaded in similar fashion to the Rolligon rollers, and driven by means of the chain connecting their axles. The basic concept is old but has taken on new significance through the availability of Terra-Tires, so that the circulating wheels may have reasonable ground pressures as wheels and also provide a degree of suspension action. Small vehicles employing this type of propulsion [Automotive Industries, 1 Dec 1962] are under study by the U. S. Marine Corps [Kyle, 1965; Beller, 1966]. WES trafficability tests of an early lash-up [Rush and Rula, 1961]



Mather Rolligon vehicle, 1964



Proposed 50-foot field-erected tires

and cross-country tests by the Marines of a more refined version [USMC, 1965] have shown the Airoll track to have excellent performance in extremely soft soil conditions, muskeg, etc., although overall their basic performance level appears to be similar to that of a good, low ground pressure, tracked vehicle such as the M116 or the articulated XM571. A clever variation on this theme is the toy-size Canadair Fisher vehicle [Canadair, 1964].

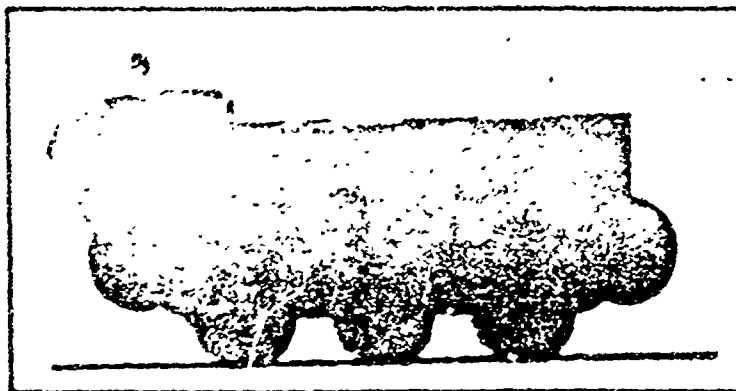
On a firm surface the track rollers roll between the ground and the ponton with a superficially fascinating 2:1 overdrive effect; i.e., ground speed (if there is no slippage) is twice "track" chain (or axle) speed. In very soft going, the Airoll system converts itself into a relatively normal track having a small number of very large but not truly aggressive grousers, which are the wheels, and the wheels then slip, on the ponton or on the ground, rather than roll. However, except on hard, slippery surfaces, their external performance (not considering efficiency) is good [USMC, 1965].

A further variation of this theme (i.e., to roll on small wheels in good terrain and to work with a large wheel having large grousers in bad) is the Lockheed star wheel proposal by the Forsythe brothers [The Engineer, 1 Oct 1965; Automotive Industries, 15 Apr 1965]. In this configuration a large "wheel" carries three driven minor wheels, and drive may selectively be supplied either to the smaller minor wheels or the entire constellation, as necessary. While there has thus far been no publication of a drive mechanism, it is tempting to carry this configuration to Albee's friction

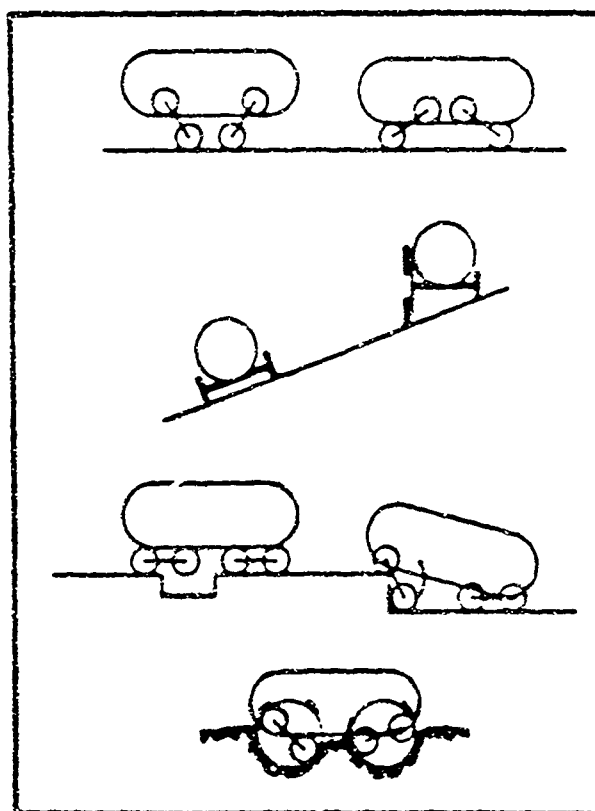
Rolling-drive, in such a manner that the minor wheels would be driven, by skin friction, by means of a central sun wheel. The major wheel could then be driven when needed by simply locking the minor wheels and running the sun wheel in a low geared reverse.

The Northrup two-wheel "walking bogie," apparently conceived independently of the Forsythe star wheel, is in some respects functionally a two-wheel version of it. In this concept, the vehicle is supported on four two-wheel bogies. In normal operation the wheels are driven and the bogies float, and the vehicle is an 8x6. Under special circumstances the bogies may be rotated and locked in such position that only four wheels are in contact with the ground (two wheel bases are possible); or, as still another, the bogies themselves may be driven about their pivots, to aid climbing, or to provide, similarly to the star wheel, a large wheel with a big bite and a bumpy ride [Lee, 1966].

A totally different series of developments has been born of the successful demonstration of hovercraft, air cushion vehicles (ACV's), or ground effect machines (GEM's). The GEM itself is, of course, immediately a candidate for off-road service, particularly where the ground can support only the most modest loadings [cf. Sickles, 1965; Fuchs, 1966]. GEM's have been successfully demonstrated for Greenland ice cap use [Abele, 1966] and for high speed military patrol work on the rivers of Borneo [*Hovering Craft & Hydrofoil*, May 1966] and Vietnam [*New York Times*, 15 May 1966], for example. Although skirting developments have reduced power requirements to approximately 20 HP/T for hovering [*Hovering Craft*



Canadian Fisher, 1964



Northrup walking begin, 1964

a Hydrofoil, June-July 1960], numerous problems with slopes, obstacles, even moderately-close-spaced trees, just, ingested sand, etc., remain to be solved. Current thinking seems to be that their most immediate military usefulness will be in amphibious operations, such as for high speed transport on long over-the-water ship unloading jobs [Bees-Allen, 1963]. The situation with GEM's is still changing rapidly. New possibilities for exploiting the Coanda effect to reduce power requirements -- and hence to ameliorate all current problems -- recently suggested by Reba [1966], for example, may drastically alter the picture within a few years.

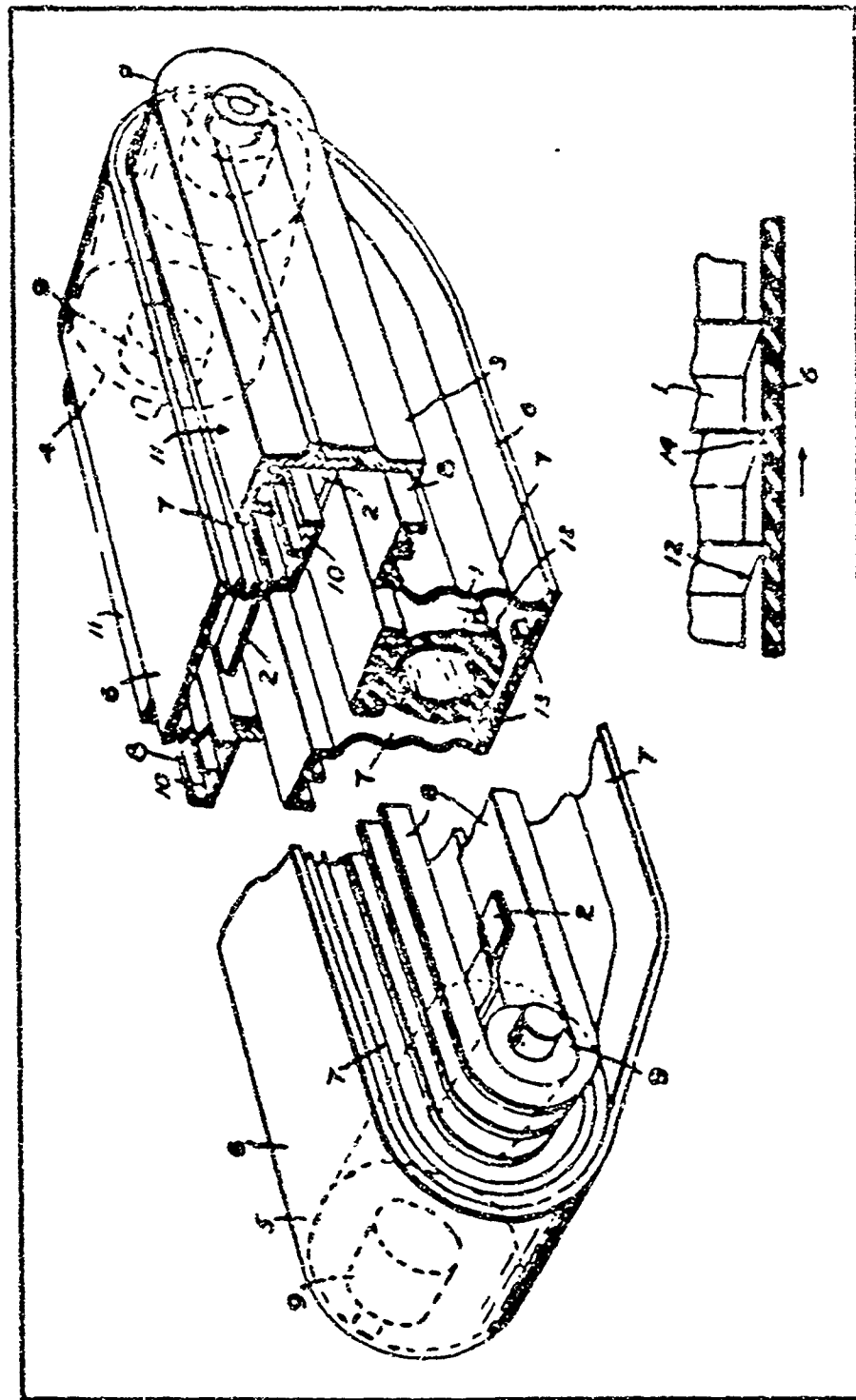
In an effort to overcome some of the current disadvantages of GEM's, in off-road terrain (and on the road as well), numerous hybrid GEM concepts have been proposed, in which the hovercraft type of air support is supplemented in adjustable degree by more normal ground-crawling gear, generally wheels [cf. Bertelson, 1963; Genini, 1964]. These have not yet proven particularly successful [Sickles, 1965] and a study by Uffelsmann has indicated that they are not likely to be [1966]. One area of possibly successful hybridization, however, might be in the development of a GEM ferry for military use, designed to operate over roads and trails simply as a relatively normal 10-12-foot-wide truck, with side plenums folded up to form a deck cargo, and to operate over water as a true GEM with a width of 35 ft or more.

A second line of development which began as a result of GEM experience is the air supported track [cf. Bertelson, 1963; Hardy, 1964], which may be considered a hybrid of a different style. It is currently

exemplified by the PATA vehicle [1966], whose design was initiated by the U. S. Army Transportation Research and Engineering Command in 1959. This vehicle carries a track which, between the sprocket and idler, is pressed to the ground by the vehicle's weight through a plenum air chamber, the lower side of which is the flexible back of the moving track belt. This eliminates the road wheels and springs of a normal tracked vehicle and, if the track were ideally flexible, would provide a nearly uniform contact pressure throughout the contact area regardless of reasonable ground roughness, a situation both theoretically and practically to be desired.

Problems arise in "sealing" the air chamber which, because of the difference in pressures (approximately 1.5 psi on the PATA vs. 0.2 psi on a GEM), must be solved quite differently than on a true GEM. The basic PATA concept appears functionally competitive with Bekker's earlier fluid-lubricated skid track on a pneumatic ponton [1953], which has never been seriously tried "in metal," largely because its sealing problems appeared difficult.

On the PATA prototype, apparently as a part of the solution to the sealing problem, the air-supported-tread concept is combined with one of pneumatically inflated elements between the track belt and the ground, basically similar to that of a Japanese marsh vehicle of the early 1940's [Neville, 1954].



Bekker lubricated skid track, 1950

In prototypes of both the Airell and the PATA concepts,* the space required to accommodate the running gear is relatively very large. In assessing their performance in soft soils, the advantage of the low nominal unit ground pressures which characterize them both must be taken into account, and only the residual improvement credited to the new elements, and balanced against their space, weight, and other costs.

Two more unusual developments in running gear configurations require mention: walking vehicles and archimedeas screw-propelled vehicles. Neither type is new.

The very first WWII concepts (1942) for the vehicle which subsequently became the Weasel were based upon archimedeas screw propulsion (OSRD, 1946), in part because several vehicles on this general pattern were then reported to have been successful in deep snow operation. This approach was dropped because of obvious problems when operating in firm terrains. However, the idea will not die (cf. Cole, 1961).

The current revival of interest in archimedeas screw vehicles centers upon the Chrysler/ARPA/ Buships 3/4-ton payload amphibious Marsh Screw, designed in 1962 for infantry support in the wet delta areas of South Vietnam (Neumeyer, 1963; Neumeyer and Jones,

*In passing, it is suggestive that the Airell, the PATA, and the major/minor wheel concepts are now being promoted by what are basically aircraft companies, as was the Camo Coat. However, it is also suggestive that the untrammeled, imaginative aerospace industry, given responsibility for moon vehicle designs, overwhelmingly proposed machines (33 out of 67) on wheels (Romano, 1965).

1965]. On this skid-steered vehicle the two counter-rotating rotors are large enough to float the vehicle at its gross vehicle weight with its hull clear of the water. As a direct result, its water performance is good (8 mph), and as an indirect (but not accidental) result, its performance in mud and weak, wet terrains is excellent. S. D. Jones points out that its "spectrum of performance is almost the reverse of that of conventional vehicles" (1964): i.e., it performs best in the wettest conditions (including clear water) where trucks are poorest; worst on-road, for example, where trucks are best [Knight et al., 1964]. Since much of the basic indigenous Vietnamese transport system in the Mekong delta is based upon canals rather than roads, this vehicle's reversed spectrum might have made it useful to the troops in much the same manner that the "jeep" is in more normal situations: able to move well in the canals, with considerable but not unlimited mobility in "off-canal" terrain. Seeking perfection rather than utility, and mindful of the ambush problem on the waterways, which is similar to that on the roads [cf. Smith, 1966], a series of stateside committees, in early 1964, decided upon further research rather than production. The concept is now being researched to death [cf. Dugoff and Ehrlich, 1966].

Despite the fact that man does not fly by flapping his or any other wings, or propel his boats by sashaying his tail about, there are many who feel that our off-road vehicles would be vastly improved if they functioned more nearly in the fashion of nature's successful land-going models. Walking machines of various kinds and all sizes appear regularly in the patent literature beginning over

one hundred years ago [cf. Nicholas, 1840]. Nonetheless, except on huge strip mining plant as described by Kamm [1966], and T. Tucker's monstrous NAVCERELAS walking barge for the seabees (1950), the pure walking mode has not been used in practice. Poché employed "steppers" working in conjunction with wheels on some of his marsh buggies, which in marginal going augmented wheel traction for a brief period during each revolution [Nuttall et al., 1954], but this was at best a poor hybrid. There are, however, reasons, stemming from terrain-vehicle relationships, for looking into the matter in light of recent technology [Shigley, 1960, 1961; Liston, 1964, 1965; Hain, 1966].

Recent and current studies have taken two different, fresh tacks: the multileg or centipede approach [Siddall, 1964] and the biped approach [Liston and Moser, 1963]. While apparently feasible, the wave-motion multileg approach is not now exciting any real enthusiasm, but the man-stabilized biped or quadruped concept, cleverly capitalizing on recent servomechanism developments to utilize a man (the driver) as the necessary balance and control computer, is gaining adherents [cf. Hemion, 1956]. The AT&T Land Locomotion Laboratory is supporting hardware research with General Electric, aimed at having a 500-pound load carrier in operation within a few years [Science Journal, July 1966]. Liston has estimated the cross-country speed potential of the biped configuration at 30 mph. Unfortunately, the concept appears useful only for relatively small special purpose machines, in which it may overcome many of the nasty problems with obstacles which bedevil more normal small vehicle configurations.

Related to the walking concepts, semantically at least, are hybrid vehicles which incorporate means for "jumping" or for "inching" in special situations. A concept for a jumping 4x4 armored car, which, for obstacle negotiation, could theoretically make a running leap of several vehicle lengths through the release of energy stored in its wheel suspension system, was studied during WWII [OSRD, 1946; Icks, 1965]. The investigation was carried only to the point of tests of a single wheel and suspension mock-up. Problems with precise launch control, upon which flight and hence successful reentry performance depends, were not solved before the project was suspended. Feasibility of a "jumping jeep" has recently been reported to have been established, and serious design begun by the British War Office [The Engineer, 25 June 1965]. The project is classified and no information has been released as to the approach taken. (It could well be an air-cushion vehicle.)

"Inching" describes a proposed mode of locomotion for vehicles vaguely resembling that of the friendly little inchworm, who anchors his front half, hauls in his rear, then anchors his rear and pushes forward his front, etc. Provision for such a behavior may be incorporated in the joint of a frame articulated vehicle [VMA, 1965]. It may also be done by so mounting the wheels on a machine that they may be moved fore-and-aft in relation to the vehicle's body, and braked in an appropriate cyclic manner as proposed by Schröter et al. in their thrust-step patent [1963]. Inching is basically a slow process, and has been proposed largely as a built-in self-recovery system for use in case of bogging. Its function is thus similar to that of a winch, or the capstan and anchor system now regularly

used as a mobility aid to M113's for getting out of the canals of Vietnam [Moore, 1966]. As an auxiliary, its speed should be about the same -- 3 miles per day; its convenience greater; but its usefulness on extreme and/or slippery slopes far less.

Finally, while neither new nor unusual in the sense of previously discussed concepts, the development over the past ten years of hydropneumatic tank suspension systems and deep, soft, adjustable suspensions generally, and the work on active systems [AMC T12 CD-11, Supp. II, 1964; ATAC, 1965; Osborn et al., 1965], requires mention. These hardware programs are opening the way to tracked vehicles with operational speeds in rough terrains two to three times as high as those of current machines, should these truly be desired [ATAC, 1965]. They are demonstrating not only what may be done but also what the costs will be. The full value of these developments, however, will not be apparent until they are applied to properly designed articulated tracked vehicles where, combined with significantly greater effective wheelbase, they could permit truly astonishing performances. Such a further program does not yet appear to be in the cards, however.

Articulated Vehicles

Although not as eye-catching as some of the running gear configurations just reviewed, the most significant recent off-road design development has been the successful, practical demonstration of the feasibility and overall mobility advantages in all types of weak soils and difficult terrain generally of frame articulation, particularly on tracked vehicles. The idea, again, is not new. Its history has been summarized by the author in relation to wheeled vehicles [WNAE, 1963] and tracked vehicles [1964], and by Ogertievici [1963, 1964]. Yaw-plane or steering articulation has been widely used on wheeled earthmoving scrapers for many years. Bekker was the first to recall to today's off-road vehicle designers some of the advantages of articulation when applied to tracked vehicles [Johnson et al., 1931; Bekker, 1953, 1954]. He has since been imaginative in applying the multi-articulated concept to potential moon vehicles, some of which achieve some of the functional advantages of articulation by the use of highly flexible frames [Bekker, 1962, 1963; Lee, 1966].

A vehicle's frame may be articulated, or jointed, at one or several places. Each joint may allow relative motion between connected units in the pitch plane, the steering or yaw plane, and/or about a roll axis. The uses and advantages of articulation vary with the particular motions permitted.

Articulation in the yaw plane is generally done to provide steering, through control of the articulation angle by hydraulic or other means. It is useful on wheeled vehicles because it permits

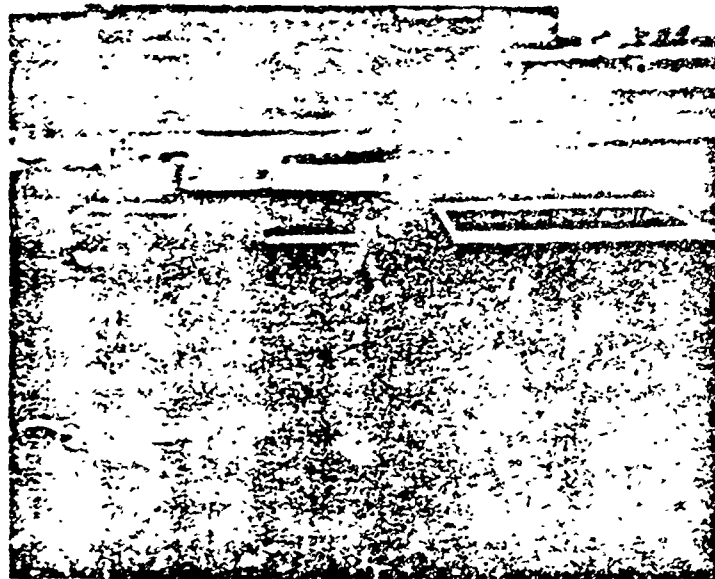
the use of really large tires, which if steered as on normal vehicles by axle articulation would require large cavities in the vehicle envelope, necessitating enlargement of the envelope or a severe reduction in usable space. It also somewhat simplifies the drive (and suspension, when fitted) to those wheels which would otherwise be steered. The space advantages and drive line simplification also make practically feasible the use of many more driven wheels under a vehicle at the minor performance expense only of some tire scuffing. Examples of yaw articulation thus exploited are the ATAC 8x8 Quad Truck [Bischoff, 1964], the VASA 10x10 concept [1965], and the small Lockheed 12x12 [The Military Engineer, Sep-Oct, 1965].

Steering by controlled yaw articulation is even more important on tracked vehicles, because it breaks the "steering barrier." In conventional tracked vehicles, whether construction tractors or tanks, the requirements for steering impose limitations on the overall proportions which are not always favorable from an off-road viewpoint. The normal tracked vehicle is skid-steered; i.e., change in heading is accomplished by changing the relative speeds of the two tracks and thereby developing turning moments to overcome resisting forces, principally in the ground contact area. For reasonable, high speed, straight line stability, the ratio of track length on the ground to center line track tread (L/T) should be greater than approximately 1.2. In practice, in order to permit steering on a hard surface without excessive power losses, the ratio L/T should not be greater than approximately 1.8 [Steads, 1943, 1958]. On current U. S. tanks, whose capability to pivot steer is

place is clearly loved (perhaps because it is for them safer than going off-road to turn around), the L/T ratio is of the order of 1.4. European tank practice appears to favor L/T ratios of 1.5-1.6. On the successful Robin-Modwell RM-110, low ground pressure, 5-ton carrier, it is approximately 1.8.

One of the principal effects of steering ratio limitations is to force a generally "stubby" form upon skid-steered vehicles. In general, the overall length-to-width aspect ratio of conventional skid-steered vehicles is of the order of 2:1, whereas that of load-carrying trucks, for example, runs around 4. This limitation is almost eliminated in articulated tracked vehicles on which the aspect ratio may readily be of the order of 5. The very important practical meaning of this is that large tracked vehicles may be built having truly low ground pressures and narrow bellies without going to outrageous widths, and that small tracked vehicles may be given sufficient length to achieve reasonable ride and much needed longitudinal stability. Minor advantages over skid-steered vehicles of the same nominal unit ground pressure also appear to accrue in tractive capacity in snows (Rula, 1958) and in decreasing by 1-2 percent the limiting soil strength (RCI) needed for free maneuvering [WNRH, 1965].

The objects of tracked vehicle steering by frame articulation may also be achieved by the tandem arrangement of tracked tracks under a single frame, as on the Tucker Sno-Cat [1963], or by the semitrailer type of articulation as on the Robin-Modwell RM-100 [1963]. Tracked vehicles on either of these patterns are now termed "articulated" [Muttall, 1964] along with direct



Dynasite, 1965



Bekker Flex-Frame Lunar Vehicle, 1965

frame articulated machines, the articulation in these cases referring to the divided track structure rather than to the main frame.

Articulation to provide some significant degree of roll freedom between units helps the vehicle as a whole to conform closely to rugged terrain, so as to maintain its footing (for traction and control) and equalize wheel or track loadings on the ground even when no suspension is fitted. Some of the advantage of roll freedom is lost unless the running gear of each unit can conform longitudinally -- i.e., is a single axle, bogied tandem axles, or a well suspended, relatively short track. Of course, where roll freedom is allowed, each unit individually must have adequate roll stability.

Pitch articulation permits longitudinal conformance to the terrain, which is an advantage in weak soils and, more important, greatly improves vertical obstacle crossing ability [cf. Bekker, 1962, 1963; Morris, 1965] in all sizes and classes of vehicles. It also opens the way to increased water speed and bank climbing ability in swimming vehicles. A pitch joint may profitably be made lockable under driver control, so that the entire vehicle length can, when needed, be exploited in trench crossing. If further it is selectively powered, so that the ends or the middle of the vehicle may be raised under driver control, obstacle crossing capabilities and bank climbing on exiting from the water can be still further enhanced [Wilkie, 1963].

Full pitch articulation requires that the units connected be individually stable in the longitudinal plane, as on an articulated tracked vehicle, the 6x6 Camm Coat (1964), or the 6x6 D541 [Zimmerman, 1965]. In Bekker's "flex-frame"

concept, pitch freedom is restrained by spring action, either acting on a mechanical joint as on the multi-unit General Motors MARY [Finelli, 1964] or through elastic action of the frame itself as on the 6x6 surveyor GM moon vehicle concept [Bekker, 1967; 1943; Lee, 1966], making it possible effectively to provide pitch articulation between inherently unstable single axles. Pitch freedom makes no sense on 4x4 vehicles, however, and hence such articulated wheeled machines as the various GOER's do not fully capitalize on the articulated concept.

One of the major advantages of frame articulation applied to tracked vehicles of any size is that the increased length possible, even necessary, greatly improves the ride, principally by reducing pitching motions. It has been found in practice that this advantage accrues even if the pitch joint is totally unrestrained. However, still further improvements may be had through the provision of proper damping across the joint. The possibilities of applying to an articulated machine the new, deep track suspension systems mentioned earlier, which raise potential cross-country speeds of conventional short tracked vehicles from the 3-10 mph range to the 30+ mph range [ATAC, 1965], are truly exciting, particularly in a combat vehicle.

There have been numerous proposals for, and studies of, articulated tank weapons systems [cf. *Armor*, Nov-Dec 1962], but to date none has received more than passing consideration. Problems in armoring such a vehicle are evident [cf. Ogor-kiewicz, 1964]. Moreover, pending the development of suitable components specifically for application

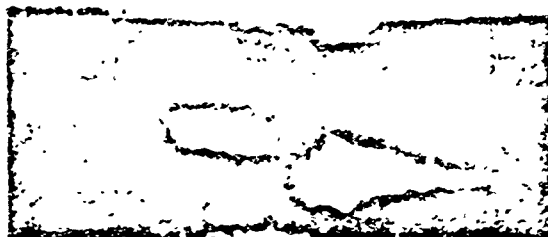
to articulated vehicles, there may be both weight and dollar cost penalties in applying this configuration to a job already within the capability of a given, well-developed vehicle. Its advantages can only be fully appreciated where a vehicle is required with a new order of mobility as compared to current machines. In this context, full exploitation of the articulated configuration may well prove cheaper, in all coins, than either the forced evolution of present forms into monstrosities or the adoption of entirely different basic running gear concepts.

The Real Problem

The ultimate basis for judging the adequacy of our military off-road vehicles is, of course, in relation to the jobs expected of them. In 1963 Bekker quoted DOD sources to the effect that "the complete gamut of tactical vehicles is inadequate . . . to properly perform their mission Neither our combat nor our logistical vehicles have sufficient off-road mobility to permit the application of current tactical doctrine." The situation has not materially changed since. Considered as a system or family of vehicles for use in the European theatre or similar geographic areas, our present machines may be near optimum when all competing factors are evaluated. Considered in relation to the support of ground operations in tropic, subtropic, and/or underdeveloped areas, they are demonstrably inadequate, with the possible exception of the low ground pressure snow vehicle derivatives, the M113 family, and the upcoming XM551 Sheridan. Even these, however, appear to be only interim solutions.

Attempts to revise our current system of vehicles to achieve the new order of off-road mobility required for these extended areas must meet with failure, because the cost in terms of other necessary features is too high. It would mean "detuning" this family so that it was no longer even near optimum for its main and original purpose. The solution lies instead in creating a new, integrated system of ground vehicles for use in these new, significantly more severe environments [Siten, 1965], a system which is not intended to supplant our current family in its proper areas, which is not competitive with it, but rather is complementary.

WWI



WWII



Deep in Korea



Vietnam



Panama Swamp Fox II



Necessary ground mobility improvements must be significant to justify the costs, as Bell has pointed out [1965]. Despite a widespread feeling that only marginal improvements are possible [cf. Davison, 1965], they can be substantial. -- especially in relation to our current levels of ground mobility in Vietnam. However, the new vehicle system needed should not be considered just "special mobility equipment" which must justify its existence on the basis of worldwide usefulness. It must be considered as a system for use in parts of the world only, large parts, but still only parts [Pearson, 1966]. After all, our current European family of vehicles does not now meet the test of military value on a worldwide basis. That is the problem.

There is thus clear need to decide whether or not we seriously intend to be capable of military ground operations in these other areas, and to decide further whether such operations are going to be conducted entirely by air or not. If we decide to have the capability to operate on the ground, we must stop looking for cheap, gadgety answers. We must recognize that a collection of toys and special purpose oddities will not do the job; that what in fact is needed is a homogeneous second family of practical, flexible, reliable, military quality, working vehicles specifically designed to operate where our present family will not. Fortunately, the fundamental specifications for such a family do not require an impossibly elaborate systems analysis. The reason we need it is simply that our European family is essentially immobile in the new conditions of interest -- ergo, a second family whose very *raison d'être* is

substantially increased ground mobility. In these circumstances, all other factors can, indeed must, be sacrificed to achieve a new order of mobility.

Current know-how, technology, and experience could produce such a family, running from cargo carriers through armored personnel carriers, various weapons carriers, to a light tank, if desired. As of the moment, it is probable that such a family would be all tracked, low ground pressure vehicles, and that all would be articulated. Possibilities for high parts and maintenance rationalization within the family (the family concept in its more usual and limited context) would be great. The job should after all start with a clean slate.

Beginning now, the current state-of-the-art would support the development of the first generation of such a family without any further research. The first generation family would not be the best possible, but good when needed is far better than best too late. Its creation would necessarily involve a number of educated guesses such as are regularly made in wartime and in commercial developments.*

If the job needs to be done at all, the first generation should get underway immediately. The current state-of-the-art would support a good, sound effort. Tackled within a proper organizational framework, including clear lines of

*The most refined systems analysis also involves similar judgments, often on crucial matters, but frequently they are less than evident because they become buried somewhere in the mathematics where, after a while, only the technicians can find them.

responsibility for the success or failure of each major phase, such an effort would automatically revitalize and redirect both terrain-vehicle research and environmental research, and would force the first-cut at a realistic, working systems analysis. The continuing research thereafter, operating under newly clarified requirements for specific kinds of information and with clear lines of responsibility for the accuracy and validity of the methods and results, would produce the information necessary for the inevitable next generation of such a family.

THE DESIGN PROCESS

It bears emphasizing that the results of research on vehicle-soil and vehicle-terrain relationships have clearly shown the directions which must be taken to improve ground-crawling mobility, and have demonstrated that there are no easy answers. Fundamental determinants of the off-road performance of a vehicle are:

- 1) its overall form,
- 2) its scale in relation to nature, and
- 3) the level of both nominal and peak unit loadings placed by it on the ground.

It is patently ridiculous to fault the research effort for such findings. They are fully paralleled by similar fundamental considerations which ship and aircraft designers have learned to live with years since. Accordingly, what requires examination and rethinking is not the research, even though this is far from acceptably complete, but the decisions which have been made in the light of the available knowledge.

The proper design of a vehicle, commercial or military, for off-road use is an exercise primarily in mechanical engineering and vehicle-terrain mechanics. The overall configuration of a vehicle should be dictated primarily by the terrain-vehicle relationships necessary to achieve the required performance. Thereafter, design or selection of its components, and their integration into a properly functioning mechanical system, is primarily

a job of automotive engineering. As in all similar problems, the requirements for each often run counter to one another and to cost considerations.

In off-road vehicle design, two fundamental requirements are invariably in conflict.

- 1) mobility in the total off-road environment, as measured by average "speed-made-good" in the performance of a mission; and
- 2) mechanical reliability when operating in the total off-road environment.

A machine which becomes a fixture in the landscape, either because of a mechanical failure or a performance failure, ceases to be a vehicle, by definition. Moreover, a vehicle is rarely, in the workaday world, an end in itself, but is rather only a means to an end. It may go and survive, and still be useless unless it can at the same time accomplish its assigned task, whether this be to move a reasonable amount of cargo or men, or to carry and fight a given weapons system.

Finally, these three basic functional requirements -- mobility, reliability, and the ability to do the assigned job -- are more often than not in conflict with other constraints such as on-road performance, transportability, vulnerability and first and/or operating costs (in one coin or another). The technical problem is, in the final analysis, essentially one of mechanical engineering, to be solved within the state-of-the-art of the

many components, subsystems, and materials available. Compromises are inevitably necessary among the many competing subsidiary requirements, even in this miraculous age.

It is the manner in which these compromises are reached which is the heart of the design process.

Commercial Design for Off-Road Operation

Commercial off-road vehicles are developed essentially on a systems basis even though the systems are generally far simpler than in the military case. Mission profile, the job to be done, even when quite broad, is relatively easy to specify. Extensive, closely parallel experience provides suitable models. The value system is simply the dollar. Optimization normally takes place not in a computer, but in the marketplace, but all of the elements are there.

A major point of departure between commercial trends and military design is in the continually increasing size of much of the commercial machinery. This has been made possible by lack of some of the constraints under which military equipment is conceived. While the primary reason for the growth of individual machine sizes is related to the economics of labor, there has been a tangential increase in their mobility as a result. This is simply a scale effect. The commercial field also permits relatively close statement of the vehicle's job description and of the specific environments in which it must work, so that more specialization is possible than is thought by the military to be open to them. This also has produced some marginal mobility gains. Inasmuch as the maximum requirement for mobility is, due to the nature of commercial operations, usually less than in the case of normal military equipment, the almost accidental net gain in operational mobility has often been noticeable.

A second major trend in commercial development parallels a basic military trend. Almost uniformly, emphasis has been upon improving mechanical performance and reliability rather than extending the range of environmental conditions in which these vehicles will operate [cf. Weinart, 1966; Hyler, 1966].

Of the several classes of commercial off-road activity, by far the most prevalent are those involved with agriculture and earthmoving. Although both types of activity are often delayed by weather conditions (earthmovers up to 50 percent of the time [Archer, 1965]), which translate into poor soil conditions, the terrain-vehicle aspect of the performance of current vehicles in agricultural and construction service is not generally considered seriously deficient. There is, however, a beginning awareness that the situation may be significantly different in areas outside of the temperate climate where most of the action has been [Burke, 1966].

Agricultural problems have provided, and still provide, the impetus for many of the practical machine-oriented soils studies. The question which led Borstein to formulate his simple soil-wheel analysis [1913] related to farm tractors, for example. The notable pioneering studies of soil motion under wheel action by McKibben [1938], the first systematic experimental studies of tire performance in soils [SAE Cooperative Tractor Testing Committee, 1937], and the considerable ground-breaking work on soil dynamics in relation to tillage problems [cf. Nichols et al., 1931-1938] are further examples. Despite this, and despite the relatively long existence of such machinery oriented research facilities as the National Tillage Machinery Laboratory [Reed, 1964] and the

Agricultural Experiment Station, University of Nebraska, Lincoln, the design of the farm tractor itself, from the viewpoint of efficient traction development, has not been notably based upon considerations of theoretical soil-vehicle relationships. Rather, the approach has been pragmatic, based upon field experience. Progress has been evolutionary, steady, and today's tractors are very effective indeed for the environments in which they have evolved.*

The situation is now changing rapidly, however, as evidenced by the numerous university and industry-sponsored soil bin research facilities springing up [Appendix I], and the growing number of papers before the ASAE on soil-traction and soil dynamics studies [cf. Reed, 1958; Ritchey, 1959; Cegnar and Fausti, 1961; Rowe and Barnes, 1961; Vanden Berg and Gill, 1962; Vanden Berg and Reed, 1962; Söhne, 1962; Forrest et al., 1962; Southwell, 1964; Siemens et al., 1965; Kuether and Reed, 1965; Reaves, 1966; Taylor and Vanden Berg, 1966; McLeod et al., 1966]. In this respect, United States efforts have fallen behind those which began just after WWII in Europe (at the National Institute for Agricultural Engineering, G. B., and the Agricultural Research Center, Braunschweig-Volkenrode, Germany, for example), but there is no evidence that our tractors in practice have as yet suffered from this lag in theory.

Current agricultural tractors are almost universally mounted on tires operating at 8-12 psi inflation. Tractor size, whether measured by the maximum sizes available, or by the average size

*It is disturbing to note, nonetheless, that it was reported at the 1965 meeting of the AIIE that in modern, high production U. S. agricultural practice, the total mechanical energy expended in preparing and maintaining the soil and in harvesting the crops from it -- tractor fuel, electrical power, etc. -- is more than the caloric value of the useful foodstuffs produced [Bergstrom, 1965].

sold, has increased rapidly in the past few years, both in power and weight [Worthington, 1966]. An increasing number of all-wheel-drive machines are now offered, some using chassis articulation for steering [cf. Buchele, 1959, Walters et al., 1960; Donnel and Race, 1964; Dreyer, 1965]. Tires on the larger machines, although still selected on a philosophy of the smallest which will do the job under "average severe conditions" [Walters and Worthington, 1955], are of physical dimensions which only a few years ago were considered to be appropriate for earth-movers. There is increasing understanding that tire tread changes can produce only minor improvements in performance once a modest self-cleaning grouser has been provided, and radial ply tires are seeing increasing use [Remus, 1965].

European farm tractor practice closely parallels that in U. S. tractors, although, for economic reasons, the largest sizes are still not being produced in Europe. Locking differentials are popular on European machines because of the slightly wetter general farming conditions and the extensive use still of organic manure [Brohm, 1965]. Serious study of farm tractors suitable for use in the significantly different environments of undeveloped countries, and particularly for rice agriculture, has recently begun [Johnson, 1965, 1966]. For the near future at least, smaller and simpler machines are indicated for such service, but the soil-related performance of current mass-produced tractors is not adequate. Solutions being proposed are no more exciting than the fitting of larger tires, however.

The size of earthmoving machinery has grown even more rapidly than that of farm tractors. Except for the omnipresent "Cat" and its competitors (whose relationships to the ground have been static for nearly 70 years), earthmoving plant is now almost entirely on large tires operating at inflations of 25-30 psi [Rodin, 1965]. Although recent studies have indicated that tire pressures may be of the order of five times the cohesion of the soil on which the plant is operating [Fenton, 1965], current practice has been optimized by experience rather than theory. The present approach to dealing with mobility problems during earthmoving operations is to alter the terrain to suit the earthmover rather than to strive for improved soft-soil performance in the plant itself; that is, the problem is solved by terrain modification (W. Jurecka, 1964). The major tire problem is one of overheating on long, relatively high-speed hauls, and tires are sized as much by this consideration as by soil considerations, within the general inflation constraint [Clendenen, 1959; MacFarland, 1964; Burks, 1966].

While, from the soil-vehicle relationship viewpoint, the design of earthmoving vehicles has been based entirely upon practical experience, this situation also is changing [cf. IME, 1965]. The industry sees its major jobs as still ahead [Eberhard, 1964; Burks, 1966]. And still bigger machines. According to LeFournais, "There are no big jobs, there are just small machines" [James, 1966]. Earthmovers with an aggregate installed power of the order of 1000 HP are not new unusual, and still larger power plants and necessary drive line components are under development.

As the equipment has become ever larger, there has properly been increasing concern with its efficiency and both the vehicular and the earthmoving parts of the system are coming increasingly under systematic study [cf. Nelson and Selig, 1964; Osman, 1964; Hettiaratchi, 1965; Little, 1965; Payne et al., 1965; Reece, 1965]. In addition, the construction equipment industry is now supporting a number of in-house engineering research efforts in the earth-moving soil mechanics field, of which the Caterpillar effort is the most prominent [Cobb et al., 1961; Sullivan, 1964; Cohen, 1964]. The ride dynamics of earthmovers is also coming under study [Burks and Carter, 1966; Liljedahl, 1966; McGuire, 1966].

A relatively new concept in earthmoving machinery is the use on the basic earthmoving vehicles of powered auxiliary loading devices, vibratory coils, etc. [cf. Hendrick and Buchele, 1963; Stuller and Johnston, 1965], to reduce the dependence of the loading operation upon vehicle traction. This is an example of the "end-run" attack on soil-vehicle problems which is sometimes open in commercial work but not, in any obvious way, to the designers of military machines.

As in earthmoving and agricultural machines, the large trucks used in the mining and construction industry have also become diesel giants, on tires, increasingly with all-wheel-drive [Cass, 1955; Burgess, 1956; Kolinger, 1957; Stornberg, 1957; Gritzuh, 1959; Eaton, 1962; Moreno and Domes, 1965; Aitken, 1966; Cashman, 1966; Kress, 1966; Lloyd, 1966]. These are, significantly, termed "off-highway" vehicles rather than "off-road" vehicles. They are designed not for cross-country work but for operations on trails and secondary roads, etc., which may be

rough and slippery and muddy but can usually be counted upon to offer some sort of firm footing. These machines are generally characterized by ruggedness [Watkins, 1965] and careful matching to the specific individual transport jobs to be done. In the design and/or selection of vehicles for this type of service, D. B. Carr (Dart) lists the governing design considerations as follows (1964):

- a) On-the-job production required of the fleet or system
- b) Haul road profile
- c) Type of materials to be transported
- d) Size and type of loading equipment
- e) Unloading requirements
- f) Environmental operating conditions (rolling resistance, adhesion, altitude, and temperature)
- g) Specific requirements due to geographic location (availability of various types of maintenance equipment, training level of drivers and maintenance technicians, stature of operating personnel, etc.)

Suitable secondary road construction and maintenance are assumed. Basic design priorities, after performance is assured, are:

- a) Safety
- b) Availability (which includes both mobility and reliability)
- c) Serviceability

Tire sizes are selected both from the viewpoint of vehicle performance and of road maintenance.

Tire costs constitute the major single component of operating cost for vehicles in mining and quarry work, and on a 40-ton payload truck, maintenance and repair as a whole may run to \$4000 per month. This class of machine is currently powered with approximately 6-7 HP/T GVW, operates

at costs of about 5¢ per ton-mile of payload carried one way, with a fuel consumption of 400 ton-miles of payload per gallon of diesel fuel. Life of these vehicles is of the order of 10 years, or 50,000 hours of operation. Models for computer optimization of route layout, vehicle characteristics, maintenance programs, etc., for such fixed route operations, are now in use [Pratt, 1965].

Related to these machines are the generally smaller, but still large, rugged trucks used in more general off-highway transport service by oil companies, logging companies, etc. These vehicles are even more closely related to their on-highway cousins than to their big brothers, although various special features such as oversize tires, all-wheel-drive, heavy duty radiators, etc., raise their cost by a factor of 2 or more [Kerr, 1956]. Brown and Dorsey (Kenworth) list considerations for this class of truck as follows [1960]:

- a) Installed power should be 5 HP/T or more
- b) Flexible, high deflection tires should be used to give nominal operating inflation pressure of approximately 30 psi
- c) Suspension system and frame should be designed to equalize ground contact pressures among the tires
- d) Radiator capacity must be adequate for long, full power hauls at ambient temperatures
- e) Proportioning interaxle differentials should be used to provide proper torque allocation among all driving wheels at all times

Brown and Dorsey stress that the most troublesome problem is concerned with the physical and mechanical accommodation of adequately large sizes.

The French firm Berliet, from 1958 to 1962, demonstrated the feasibility of truck convoy operations across the Sahara Desert (Berliet, 1964). On several traverses of up to 1500 miles, the 700 HP trucks used each carried approximately 100 tons of payload and covered 100 to 150 miles per day. Berliet considers that reliability, comfort, handling, safety, and noise level are prime factors in the design of a vehicle for this type of service.

There is a growing market for rugged, medium-size off-highway trucks for daily use upon the trails and secondary roads which predominate in undeveloped countries. This market essentially overlaps the 3/4 ton to 10-ton military truck field. B. D. Irvin (1964) considers that the key to a successful commercial vehicle in this field will lie in the provision, at "a dollar a pound," of a suitable high-travel, low-rate suspension system to protect the vehicle, cargo, and road at relatively higher speeds than are possible either with current trucks of on-road lineage or with M111-style military trucks in this general size class. Unfortunately, the desired reconciliation of the cost of providing such a suspension with an economically viable consumer price has yet to be made, either for the civilian or the military. Japanese manufacturers are looking closely, but (so far as is known) unimaginatively, at this market (Kawada, 1965).

True off-road vehicles in commerce having performance in difficult terrain of the order of the more able military vehicles, or better, are limited primarily to those in use by the oil industry in their exploration work in such extremely difficult terrains as marshes, swamps,

etc. Numbers required are, by normal production standards, limited. As a result, the supply of such machines has been left largely to small specialists firms. These groups have each generally developed several imaginative vehicles, often unusual in size or appearance and often tailored to a relatively narrow range of conditions [Robin-Medwell, 1963; Tucker, 1963; Quality, 1964; ARICO, 1964]. Some of the marsh buggies -- beginning with the 1939 Gulf 4x4 on 10-foot tires [Jacobson, 1945] and now exemplified by various lightweight frame machines utilizing four large Terra-Tires or wide, aluminum slat, ponton tracks -- are the "monstrosities" to which Philippe has referred [1964].

The design approach to all of these machines has been entirely straightforward and untheoretical. The requirement for uninterrupted mobility while doing the job to be done in the problem terrain comes first and foremost. Mobility in a specific situation cannot be faked, and the problem area cannot be avoided. Accordingly, any and all constraints which conflict with these requirements are relaxed as necessary. Choice of which constraints to be loosened is entirely up to the judgment of the individual designer. The final solution is often arrived at by evolution, seldom without considerable "cut-and-try" [Nuttall et al., 1954]. Cost is a major factor in the design and construction of such vehicles. Although production economies are never possible, the next best thing, the use of well developed, high production components, is fully exploited. It is in this latter area that most detailed design compromises are worked for this class of vehicle.

While the overall performance of most of the commercial special-purpose vehicles is excellent in their own special conditions, it is frequently poor in significantly different conditions [cf. Schmidt, 1949]. Moreover, neither the limited market for these vehicles nor the resources of their several manufacturers will support the elaborate engineering and development efforts which regularly go into military and production commercial designs. As a result, the reliability, even of those built over the years in some quantity, is generally considerably less than desired by the military [cf. USATB, 1962]. It is particularly poor when the vehicles are used in terrains for which they were not designed and subjected to the calculated abuse which appears to be a major feature of evaluation by the military of this kind of equipment [cf. Swamp Fox I, 1962].

Labor economics have resulted, in the past ten years or so, in the development of some highly mobile logging equipment. This work began in Canada in about 1950 under the auspices of the pulpwood industry. After many years of experiment in the field, the general pattern of these machines is now set. They are short-coupled, large-tired 4x4 vehicles, steered by frame articulation, and are exemplified by the Canada Car "Tree Farmer" [1964] and the Koehring-Waterous "Forwarder" [Design News, 10 Sep 1964]. Unlike the military GOER's, which may owe somewhat to them, they have adhered more closely to low tire loadings and this, with their close-coupled configuration, gives them higher "go, no-go" mobility, more in line with the potential of the large-tired articulated 4x4 concept. Like the GOER's, however, they are, in the

interests of ruggedness, simplicity, and spare, unsprung. As a result, their progress through the timbered land for which they were designed is slowed to a crawl by their rough ride in crossing stumps, slash, rocks, etc.

Despite the latter performance limit, these machines are considered satisfactory and are revolutionizing the pulpwood industry. They are now being sold, at \$30,000 to \$50,000 per copy, depending on size and the extent of integrated timber handling equipment, at the rate of approximately two thousand per year (C. R. Silversides, Abitibi Power & Paper Co., Ltd.). In Canada, modifications of this type of machine are replacing small commercial tracked vehicles, such as built by Bombardier and McDowell, in many other moderately difficult off-road jobs, in which, although their ultimate off-road performance is somewhat less, their maintenance and operating costs have proven to be some 75 percent lower. The net result is a reduction in overall operating cost of approximately 20 percent, and the trade-off is considered a good one (Campbell, 1965).

There is a growing market, particularly in affluent America, for various types of off-road sports vehicles (cf. Gilbert, 1966; Cantwell, 1966). In this country, Willys, Ford, and International Harvester now offer small jeep-size 4x4 vehicles for sport or work. Fifty-five thousand such vehicles were sold in 1965 (New York Times, 29 Aug 1965), and Ford estimated that its "Bronco" would account for one percent of their vehicle sales in 1966 (Axelrad, 1966). In the considerable market for this type of machine in less developed countries, where jeep-type vehicles are strictly utilitarian, these U. S. vehicles compete with the

more rugged and better arranged British Land Rover (which also offers a diesel engine), the Mercedes Benz Unimog line [The Engineer, 29 Oct 1965], and similar size Japanese vehicles [Iritani, 1965]. These small commercial 4x4's have the same order of off-road mobility as the military jeep. In their design, this order of performance and the basically similar loadings and configurations needed to achieve it are accepted, and the engineering effort is concentrated on cost reduction, reliability, and parts rationalization, and in some cases upon making them more acceptable for family on-road use [Hartman, 1965].

There is also on the market an increasing range of still smaller wheeled vehicles, triggered by the initial excitement over the tiny, skid-steered, plastic 6x6, low pressure bag-tired "Jiger" from Canada. Many are thinly disguised copies of the original. Complementing these are growing numbers of very small tracked and ski-track vehicles essentially for snow sport, of which some 10,000 were sold in 1965 [Machine Design, 20 Jan 1966]. A1 have been designed around a clever arrangement of available bits and pieces, with a specific sports market and cost target in mind. Bischoff has cataloged a variety of current small vehicles, wheeled and tracked, which have recently been examined by the Army [1964]. None of these toys reach much, however. Both their job-ability and their basic off-road mobility are low by current military standards, particularly when conditions are severe.

The Thielkol Corporation and Robin-Kodwell have made considerable efforts to introduce some small, commercially conceived, tracked vehicles

into the military system (Spryde, *Imv.*, 24-10). In each case the design effort has consisted of accepting a desired payload, a nominal ground pressure level, and a steering configuration, which experience has indicated will generally work, and thereafter attempting to hold weights and costs in line. These tiny, nimble machines always have a certain fascination, particularly to those who were once Boy Scouts. Although their performance is good in marginal soil conditions [cf. Porris, 1964], they generally serve mainly to demonstrate the difficulty of building a small off-road vehicle which is truly mobile and a cheap off-road vehicle which is at all reliable [cf. USMC, 1965; Polar Strike, 1965]. A possible exception is the well designed, inexpensive Swedish half-ton carrier, the Snow-Trac, which, in snow work at least, appears quite good [*Polar Record*, Sep 1964]. A somewhat larger (1-1/2-ton) snow vehicle, built by Hotchkiss for use by the Expéditions Polaires Françaises in Antarctica, was unveiled in 1966 [*The Engineer*, Feb 1966], but nothing is known of its cost or field performance.

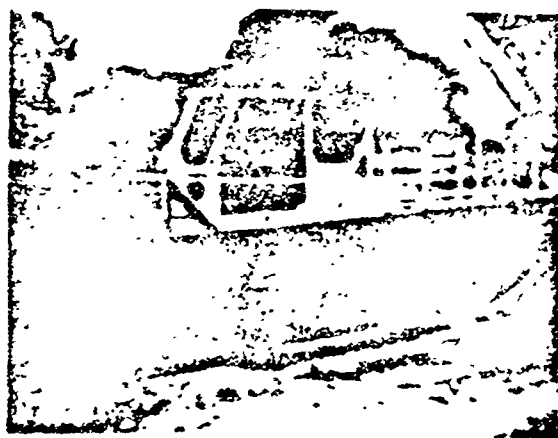
Except for some of the vehicles for oil exploration work in extreme terrains, and the ubiquitous tracked construction tractor, current working commercial off-road vehicles are almost entirely on wheels, and this discussion of design approaches has accordingly dealt thus far largely with wheeled vehicles. However, the situation with regard specifically to commercial tracked vehicles is fundamentally similar. The development of slow-speed construction tractors, which account for the overwhelming bulk of commercial tracked vehicles built, has long since ceased so far as its soil relationship is concerned. Their configuration, and even their basic ground loadings, have not

changed materially in 50 years [cf. *The Engineer*, 1917; Legros, 1918]. For the jobs for which they are intended, however, there appears to be little to be asked in this regard. In general, a variety of track widths and grouser heights are available for each machine, which permits adaptation to a wide and useful range of working conditions. Current engineering effort is accordingly aimed at increasing life and reliability, reducing first and operating costs, and improving 'styling' and operation safety, convenience, and comfort [cf. Bryant, 1966; Moore, 1966; Kahle and Hung, 1966], rather than at altering vehicle-ground relationships.



Jiger, 1963

5-TON CARRIERS



Commercial



Military

The Military Design Problem

While the design processes for civilian and military off-road vehicles deal with the same basic subject matter and necessarily have many broad similarities, there are also important differences. These relate to the scope of the problem, the value system used in making design trade-offs, the great number of tangential considerations (i.e., other than primary job performance) which enter military design, and perhaps most important, the cumbersome organizational procedure by which military design is accomplished.

In the design for effective off-road operation of a military vehicle, the scope of the basic problem faced is universally far broader than in a normal civilian commercial design. The job to be done and the terrain within which it must be done necessarily are more general and hence more complex to deal with analytically than in the usual civilian situation. To the ordinary commercial design considerations must be added a number of fundamental combat considerations; and while commercial vehicles can readily be conceived which are totally unsuitable for highway use, few if any military vehicles can be accepted unless they have reasonable on-highway manners. The total design must consider not only the physical situation but, to a degree, the strategic problems of the army and current and projected tactical operational doctrine. The problem of finding an optimum vehicle configuration for the resulting unavoidably larger range of basic job and terrain conditions is proportionately more difficult.

The value system used in optimizing a military design, whether formally or, as in the past, by "seat-of-the-pants" methods, is also more complex. Dollar costs, first and operating, are of course important, but with these must be taken military values which are often unknown, even unknowable. The value of a human life, either in military or humanistic terms, escapes quantification. The dollar equivalent of extra speed, extra reliability, extra resistance to immobilization, depends in the field situation upon many factors which are continually changing. So far, not even general values are available for guidance. And the costs of training, of fuel, of parts, and of manpower all vary widely with the strategic and tactical situation. Cost/effectiveness studies are thus limited on both sides of the line. Cost is still calculable essentially only in simple commercial dollars, while effectiveness, particularly in relation to the consequences of greater or less mobility, is currently almost incalculable. As a result, current cost/effectiveness studies, where they relate to mobility, favor dollar cheapness above all else.

The number of tangential considerations which enter into the design of a military vehicle is great, particularly in comparison to those for commercial vehicles. One increasingly important group of factors is transportability, by air, rail, sea, and self-transport over the highway system [cf. AR 705-8, Dec 1954; MIL-A-8421B, 5 May 1960]. This group imposes limitations on the dimensions and weight of the vehicle which are, in most instances, entirely too real. Moreover, peacetime conditions dictate that our military vehicles be legally

acceptable on the roads not only of 50 states but of many foreign countries as well.

An additional set of critical factors is durability, reliability, maintainability, and logistic economy, importantly including parts rationalization [Bischoff, 1965]. Each of these properly exacts its share of design attention and compromise.

All systems and components are designed to bibliographic military specifications which in use myriad detailed requirements, only some of which may be germane in any given design [cf. MCV-106, 1953]. On-vehicle material, communications and human engineering problems [Hedgecock et al., 1962] and specifications must be met. Because of the inescapable inertia of the vast Army parts supply system, standard parts and components must be used to the greatest extent possible.

Personnel policy -- the general level of intelligence of the personnel who will be made available for operating and maintaining equipment and the degree of training they will be given -- must be considered.

Materials used in the construction of the vehicles must be consistent with policies for allocation of critical materials during times of emergency. Producibility is important and the feasibility of rapidly increasing production, should an item become a best seller during an emergency, must be considered. Finally, related to durability, reliability, and parts problems, the designs are generally largely influenced by the state of component development, which functions as an inertia term in the response equation.

The relative importance of the several competing design objects, primary and secondary,

tends to vary somewhat from time to time. In 1951, WWII difficulties with the workhorse 6x6 "deuce and a half" were summarized as lack of mobility (lack of flotation, axle drag and need for locking differentials), poor ride, brakes which did not function when wet or immersed in mud, high suspension mortality and high repair time [Call, 1951]. As a result, design objectives for new tactical trucks were listed at that time as the achievement of:

- 1) 60 percent gradesability
- 2) 20 percent side slope ability
- 3) fording ability
- 4) 35 mph minimum road speed
- 5) 300-mile minimum range
- 6) air-transportability
- 7) maximum ground clearance
- 8) low silhouette
- 9) run-flat tires
- 10) locking differentials
- 11) be operable on 72 octane fuel
- 12) be operable at -65 to +125 degrees F.,

all in vehicles characterized by a minimum use of critical materials, minimum cost in volume production, and available with kits to adapt it to special uses. In 1953, the multifuel objective was added [Miller, 1953].

In 1959, Lynde listed objectives in tactical truck design as: significantly improved mobility, austere logistic support, improved maintainability, and a 100-percent increase in durability and reliability to 20,000 miles without depot overhaul for wheeled vehicles and 4000 miles for tracked vehicles. Bischoff, in 1962, listed the priorities in relation to tactical military trucks as follows:

- 1) Functional design
- 2) Off-road mobility
- 3) Durability and reliability
- 4) First cost and producibility
- 5) Performance in environment
- 6) Maintainability
- 7) Air transportability
- 8) Floatability
- 9) Economy of operation

The 1952 priorities set for the conversion of the Gama Cent to the XM561 were: performance (especially cross-country, while fulfilling its "intended purpose"), durability and reliability, maintainability, transportability, economy of operation, simplicity of design, minimum weight consistent with the foregoing, and suitability for both low and high production [REPD 62-22, 1942].

In 1943, Liston, somewhat parochially, saw improvements necessary as follows: improved floating ability and improved ability to negotiate riverbanks, improved ability to operate in areas that are presently obstacles to off-road trucks, an increase in operational off-road speeds by a factor of 4, and improved weak-soil performance, maintaining, the while, full air transportability.

Most recently, in speaking of the COER program, Harshfield [1965] ordered priorities as follows: transportability, maintainability, ruggedness, durability and reliability; and Moore, in discussing 5-ton truck developments, listed the problems as "misuse, abuse, neglect, and mud," and put the priorities: performance, reliability, durability, minimum maintenance, ease of maintenance, configuration, transportability, and kit availability. Current maintainability goals for tactical trucks have been raised to a 90 percent capability of going 10,000 miles with only unit support, 20,000 miles with only direct

	Power Train	Gradability	Flexibility	Integration System	Mobility	Type of Fuel	Support Requirements	Kit Requirements	Payload	Weight	Physical Size	Overall Cost
Environment	X	X	X	X	X		X	X	X	X	X	X
Mission Requirement	X	X	X	X	X	X	X	X	X		X	X
Speed	X	X	X	X	X		X		X	X	X	X
Range	X			X	X	X	X		X	X	X	X
Physical Size	X	X	X	X	X		X	X	X	X		X
Weight	X	X	X	X	X		X	X	X		X	X
Reliability	X		X	X	X		X	X	X	X	X	X
Recoverability	X	X	X	X	X	X	X			X	X	X
Armor	X	X	X	X	X		X	X	X	X	X	X
Transportability	X	X	X	X		X	X	X	X	X	X	X
Initial Cost	X	X	X	X	X	X	X	X	X	X	X	X

Fig. 4. Primary function versus feature interrelations

	Mobility	Payload	Speed	Range	Size	Weight	Reliability	Recoverability	Armor	Transportability	Initial Cost	Value
Reliability	X	X	X	X	X	X	X	X	X	X	X	10
Payload	0	X	X	X	X	X	0	X	0	X	X	6
Speed	0	X	X	X	X	X	0	X	X	X	X	8
Range	0	0	0	X	X	0	X	0	X	X	X	5
Size	0	0	0	0	X	0	X	0	X	X	X	4
Weight	0	0	0	0	0	X	0	0	0	0	0	9
Reliability	0	X	X	X	X	X	X	X	X	X	X	9
Recoverability	0	0	0	0	0	X	0	X	0	X	X	3
Armor	0	X	0	X	X	X	0	X	X	X	X	7
Transportability	0	0	0	0	0	X	0	0	0	X	X	2
Initial Cost	0	0	0	0	0	X	0	0	0	0	X	1

Fig. 5. Interrelations of design goal.

support, with a total of only 75 hours of unscheduled maintenance [Moore, 1965].

All the various requirements, whether basic or tangential, are interrelated in various ways and degrees. Figure 4 displays a very preliminary check matrix showing areas where strong interrelationships usually will be found to exist [Siten, 1965]. It is clear from this diagram that overspecification can quickly freeze a design to the point where the vehicle engineer is left no choices, or even to the point where all basic requirements cannot in fact be met. Siten has also suggested the usefulness of an additional matrix (Fig. 5) giving general priorities to be followed in making the trade-offs during the design process. (His display, as will be seen, greatly favors mobility, but he does not present the basis for its construction.) Even with such guidance, however, it is apparent that amidst such a welter of considerations of varying importance, presented usually in varying degrees of quantification and detail, the basic but amorphous considerations which relate to the job to be done, the very *raison d'être* for the entire machine, may get lost in the shuffle.

The final and probably most important difference between the military and the commercial design approach is the lengthy, complex, and cumbersome procedure by which a military vehicle proceeds from requirements to issue, which tends to compound difficulties at least as much as it is intended to reduce them. This facet of the problem is outlined in the section following. Suffice it is forecast at this point that the number of people involved, the number of voices which must be heard and satisfied, the interlocking politics involved, are vast. Committee upon committee makes its contribution, while there is no one truly responsible for the overall result at any time. One pivotal upset is a time delay between

initiation of a request for improved equipment and its final production which has reached as much as ten years. Partly as a result of the long time delay, partly as a result of the committee approach, priorities and goals change during the course of development. The problem has been likened at the technical level to one of firing upon a moving target [Razay, 1964].

Beyond all of these problems, which relate to the conception and delivery of a single design of vehicle, is the simple, long recognized fact that one vehicle does not make an army [Martelli, 1931]. The mobility of an army depends upon a complete system of vehicles. The addition of one supermobile machine to an existing system of essentially road-bound vehicles can have but little impact upon the total situation. Recognition of this factor adds further inertia to the design process, making it ever easier to favor mobility solutions which do not alter the status quo in preference to the more radical solutions which alone can produce marked improvements. (In fact, the order of gain in mobility desired at this time can probably only be achieved by starting fresh to develop an entirely new system, unfettered by the lack of mobility of any or all current machines.)

The Basic Military Vehicle Development Route

"The overall program . . . has become much more complex in the past ten years or so."

- Harrison, 1963.

In order to understand some of the problems which currently confound the creation of new, more effective military vehicles, it is useful to trace the route by which a requirement is developed [Muller, 1964] and perhaps ultimately fulfilled, and to meet the incredible number of people who will have their fingers in the pie before it is done.

One of the major features of the Army reorganization of 1962-63 was the consolidation of basic systems and equipment development and procurement largely under the Army Materiel Command (AMC), and the centralization of the combat development functions of all arms under a single Combat Development Command (CDC) [Harrell, 1963]. The complete system is designed to deal with anything from a paper clip, Mark III, to a worldwide anti-antimissile system. Briefly, in relation to vehicles, it works approximately as follows.

Need for a new vehicle may be suggested by any of numerous sources, including field forces. R&D groups, the several training commands, or various echelons of CDC itself. Each such suggestion is forwarded to CDC, which reviews it in relation to the Army's long-range plans and future requirements. CDC review includes evaluation by its

appropriate service groups and field operations agencies (such as the Service Support Group and the Transportation Agency) and informal coordination at each level with interested service schools and boards. A primary object is to establish whether or not there is a bona fide need.

If this is agreed to, the proposal is sent back to CDC through channels, and there is made by CDC into a request to the Office, Chief of Research and Development (OCRD) to establish a Qualitative Materiel Development Requirement (QMR) for the item. The proposed QMR will generally include the following:

- 1) statement of requirements
- 2) operational, organizational, and logistic concepts
- 3) justification, feasibility, and priority
- 4) characteristics
 - a. performance
 - b. physical
 - c. maintenance
 - d. human engineering
 - e. priority of characteristics
- 5) personnel and training considerations
- 6) associate considerations
 - a. training devices
 - b. special tools
 - c. kits (to be developed concurrently)
- 7) cost target

In order to give AMC time to think about the problem, to begin determination of its technical feasibility, and to check on cost and performance targets, the proposed QMR may be coordinated with

AMC and its automotive development agency, the Army Tank-Automotive Center prior to its forwarding to OCRD. Coordination with overseas commands, the Continental Army Command (CONARC), and other services and when necessary, allied armies, may also be undertaken at this point.

Upon receipt of the request from CDC, OCRD examines it for, among other things, technical feasibility, and may pass or reject it, recommend further study, or suggest that it be forwarded to the Assistant Chief of Staff for Force Development (ACSFOR) for longer-range consideration as a Qualitative Material Development Objective (QMDO). If accepted by OCRD as needed and presently feasible, it becomes a CDR (or perhaps an SDR -- Small Development Requirement, which is essentially a junior CDR). Should its development require substantial new money, however, it is referred by OCRD to the Material Requirements Review Committee before it finally becomes a CDR. This committee is a permanent Chief of Staff function composed of deputies to ACSFOR, Deputy Chief of Staff for Logistics (DCSLOG), and OCRD, with CDC, AMC, and Deputy Chief of Staff for Personnel (DCSPERS) representatives as regular non-voting participants. In practice, about 50 percent of the items passed by OCRD do not require this review because the money required can be handled under existing, funded programs.

If approved through this point, the proposed requirement becomes a bona fide CDR and is entered into the Combat Developments Objective Guide (CDOG) along with many, many others. It may now be funded, when and if its priority rating is sufficient in relation to total available funds.

Up to this point the proposed new requirement has been evaluated on numerous levels:

- 1) at the originating agency or individual's level
- 2) at Combat Developments Command Staff level
- 3) at CDC Group level
- 4) in the various CDC Group agencies
- 5) in the Army Materiel Command (at various levels)
- 6) in the Field Armies
- 7) in some other services, and
- 8) in some cases, in foreign military services

In fact, at many of these levels there are two opportunities for evaluation: on the way down through the chain and again on the way up after comments from lower echelons. In addition, there are inputs from the necessary cross-coordination between groups at the same level.

Evaluations at each level consider the following points, in various degrees:

- 1) Is there a real need?
- 2) Is there a like item already in the system?
- 3) Are commercial items available which will do the job not as well but in an acceptable manner?
- 4) Is the item technically feasible?
- 5) Is the tactical or strategic concept which envisions use of the item sound and definitely in immediate, interim, or long-range plans?
- 6) What are the human engineering aspects?

- 7) What is the time schedule for development?
- 8) Is the cost prohibitive or acceptable?
- 9) What features of the requirement can be changed to reduce the cost?
- 10) How will funding be handled?

The approved OMR is returned by OORD to CDC, who forwards it to AMC for final action by its technical committee. This action consists of final coordination with the other services, establishment of a basis of issue, determination of technical feasibility, establishment of funding, and assignment of the task to a development center (probably ATAC).

The responsible agency will delineate design, prototype, and production engineering problems involved. If the item is a major one, the work will usually be done through contract. Under current practice, the first step is to obtain, under a number of smaller contracts from each of several prospective developers selected through competitive bidding, a Program Definition Phase Plan. In these studies, each selected company spells out in detail the extent to which development objectives, performance, costs, and schedule can be met. These studies are intended to assure that major development projects will be undertaken only when the scientific problems have been solved and only the engineering remains to be done.

Of course, in the case of a major new development project there is always the need for approval

from the Office of the Secretary of Defense (OSD) to undertake such a development, and subsequently both the Office of the Assistant Secretary of the Army for Research and Development (ASA[R&D]) and OSD will approve the Army's Program Definition Phase Plan and award of contracts for the ensuing program definition studies. In addition, OSD must approve the selection of the final prime contractor.

The cycle to the award of a development contract may, in the case of a major item such as a new main battle tank, take 18 months or more. (The period of gestation of an elephant is approximately 614 days, but it involves fewer personalities.)

With the award of a contract, active development begins. From this point forward, responsibility for the development, testing, and procurement of the vehicle system rests with AMC.

"Preliminary designs are developed and test rigs are fabricated. The test rigs are tested by the contractor and by the Government during an Engineering Design Test phase, designs corrected, accordingly, and the development pilot models fabricated and delivered for the Engineering and Service Tests. From award of contract to delivery of pilots may take two years." *

Engineering and Service Tests are conducted for a period of approximately one year by the AMC Test and Evaluation Command (TECOM) at Aberdeen Proving Ground [Sisson, 1965]. "If all goes well, and it usually does not, the vehicle will be Type Classified

*Quotations from Morrison, 1965.

'Std A,' and it is then ready for the production phases." Frequently the prototypes are made available for limited field testing by user groups before a decision is taken, which usually leads to some further change.

"Throughout the development phase, a number of In-Process Reviews are held. These are attended by representatives of the interested Department of the Army Staff offices, of the interested Army Materiel Command offices sub-commands, and test agencies, of the Combat Developments Command and of the various interested directorates and offices within the Army Tank-Automotive Center. At each review, depending on the development phase, the design, mock-up, prototype, and test results are evaluated, discussed, and approved or disapproved. Each representative considers whether or not the interests of his agency are satisfied and, where not, compromise, coordination, and correction must be accomplished. These reviews usually do disclose gaps and deficiencies of one sort or another, and frequently result in program delays before the problems are resolved.

"The first of the production phases is the Advanced Production Engineering phase. Following preliminary programming, reviews, approvals, and negotiations, a contract is awarded (normally to the development contractor). Work in this phase includes preparation of production drawings and specifications to military standards; correction of remaining deficiencies; product improvement; value

engineering; fabrication of pre-production pilot vehicles; engineering for inspection gages and procedures, packaging, publications, and repair parts documentation, maintenance engineering; and delivery of a technical data package suitable for competitive procurement of the production vehicles.

"Pre-production pilots are subjected to additional tests at Aberdeen Proving Ground for verification of the production design. Corrections, if necessary, are included in the production drawings.

"The final phases to first production include programming, issuance of invitations for bids (now, usually on a two-step, 5-month basis), selection of low responsive, responsible bidder, award of production contract, production lead time and, at last, delivery of the first production vehicle. Concurrently with these actions, a Production Engineering Contract (PEC) is awarded, often not to the production vehicle contractor, to provide for continuation of essential engineering support after completion of the Advanced Production Engineering."

The first buy is often modest. Succeeding buys depend upon the field acceptance of and demand for the final production item. Inasmuch as the development of field demand is largely the result of exposure and experience, the "spread" of a new vehicle throughout the Army is often highly dependent upon placing a sufficient number of the new machines in the hands of units which can properly exploit them. The vehicle producers attempt to aid acceptance of their particular product through advertise-

ments in various Army-oriented journals, always with the usual Madison Avenue touch (*cf. Army, Armor, Ordnance*, any issue).

"More often than not, the time from establishment of a requirement to issuance of vehicles to the troops is six or seven years, or even more. This is too long. Obviously, decision making delays on the part of the Government can occur at many points; delays can be experienced by the contractor for many reasons; and, once the vehicles are on test, any failure can lead to down time, redesign, retest, and even a complete reorientation of the program. To overcome some of these delays, the phases outlined above are often telescoped, but such concurrency may create additional difficulty in achievement of all technical objectives. Many delays result from a lack of clear understanding of what is specifically required by or of each agency participating in the program, including the contractor." (*italics added.*)

In the context of the present study, this extended lead time has several important ramifications. The fact that the time from conception to production of a vehicle is of the order of six years or more, taken with the normal two-to-three-year rotation of officer personnel, means that the full development cycle can be expected to span two or even three changes in military personnel at each level involved, from the General Staff, through the development agency and the requesting agency, to the user boards. It is even possible that it will bridge a change in national administration, with

perhaps changes both in policy for the Army and in our international stance. While it is one of the important functions of the senior civil servants in responsible technical positions to give continuity to the detailed programs through these periods of flux, they are not always able to do so.

The result is that time and definition are lost in the development cycle through repeated variations in emphasis and even direction during its course. In large part this stems from poor communications, lack of testable specifications, and consequent lack of clear lines of responsibility for the success or failure of the finished product in meeting the actual field needs.

In the absence of quantitative expressions of required off-road performance, each person reading a QMR, for example, is largely at liberty to place his own interpretation on such nebulous (but normally used) terms as "minimum," "maximum," "optimum," etc., in relation to mobility characteristics, especially when the same document specifies quantitatively and with great care other required or desired features which are often of less actual importance to the vehicle's complete function. While this lack can usually be temporarily plastered over by a meeting of minds between personnel involved all up and down the long line, the cracks open again whenever the faces change -- as they must over so long a period.

The problem is compounded when each person is in practice free to assign his own values to the

relative importance of the competing characteristics, based almost solely upon his personal background, experience (pertinent or irrelevant) and objectivity. Again, face-to-face confrontation can establish a working consensus, but even here it can only be temporary.

The System in Action

The administrative procedures by which requirements are developed, formalized, and acted upon is supplemented on the technical side by continuing studies to explore the feasibility of new vehicle configurations and the potential usefulness of new components made possible by the rapid advance of technology. Concept and design studies, field and laboratory tests of commercial machines of interest and the construction of mock-ups goes on continuously.

During the period 1955-1962, 175 projects of this nature were conducted by ATAC in relation to logistic vehicles. In addition, during the same seven-year period, 35 "idea" vehicles were built [Bischoff, 1962]. (The term "idea" is used to distinguish these machines from those for which prior requirements had been established, rather than to imply that they were uniformly imaginative in concept.) At the same time, component development goes on continuously on all major and minor systems.

Component development is generally guided by projections of component requirements growing out of other studies. When, as has often been the case with respect to mobility, the earlier studies are unimaginative, the component work becomes a drag upon rapid response to new ideas and new situations. The results of these studies, tests, and developments are made available to those who formulate and/or formalize requirements, and sometimes become the basis for new requirements.

In recent years, under pressure from higher echelons, there has been increasing attention to parametric design studies, intended to optimize the final mechanical configurations of new vehicles. The term "parametric design" is most often associated with aircraft developments (cf. Moss, 1964). In the aircraft field it refers solely to the optimization of mechanical design to accomplish stated, clearly defined missions, in accordance with a stated value system. Development of the mission profile and the value system is the function of a prior operations analysis. By this definition, much current Army usage of the term parametric design, as in the Main Battle Tank-1970 (MBT-70) "rubber tank" studies (cf. Shiovitz, 1966), actually refers to operations analysis. Although both require the same basic information (albeit in different detail) as far as terrain and terrain-vehicle relationships are concerned, the functions can and should be separated. Whether separated or not, however, the success of the basic approach ultimately depends on valid means to incorporate both terrain and terrain-vehicle information into analyses of the total operational analysis.

In relation to the complete current design procedure, events which led to the development of the current proposed family of high mobility, tactical trucks (XM556, etc.) are illustrative of the complete system in action (Moore, 1965; Morrison, 1965). In November 1954, new military characteristics for tactical trucks were proposed. During 1957, ATAC conducted concept and idea studies, and late in 1958 the first prototypes or idea vehicles were running.

The experience with the test bed vehicles was made known to the using services who, in October 1960, produced a study [MOYER, 1960] stating that during the period beginning in 1963 the Army should be equipped with trucks which were floaters, of lightweight construction, having multifuel capability, and an increased level of off-road mobility. Following this, existing prototypes were modified and retested, and in October 1961, new military characteristics for the tactical truck line were approved.

In 1963 and 1964, contracts were let for experimental prototypes (actually "second generation" versions in light of the earlier work). By March 1966, contracts were let for final pre-production pilot models of one of these vehicles, the 5-ton XM556. That contract was of particular interest for it, for the first time, included the construction of "test rigs" [Sisson, 1963] in addition to preproduction pilots, for use by the contractor and ATAC in continuing developmental tests during the period when the pilot models were being evaluated in other areas of the system.

Response Time

Prior to the 1943 reorganization which created AMC, some sort of record was set by the development cycle for the M11 1/4-ton truck (the current independently suspended jeep [Parquette, Kraemer, 1960]), which took approximately ten years from the initiation of the project (not the beginning of the staff work to establish the project) until the first production delivery [Sibley, 1964]. Despite this great elapsed time, the resulting vehicle, which has now been in the field in quantity for approximately four years, is not considered entirely satisfactory. A program to obtain a replacement at once more austere, mobile, floatable, simpler, and cheaper is underway [RFP 64-R2-511, 1964].

The approximate time scale upon which development of several more recent cargo vehicles having improved mobility has proceeded, as reconstructed from published material, is sketched in Table VI. Times shown confirm that approximately six years go by between the establishment of a definite task and first production deliveries. Establishment of the task may in turn be preceded by several years of studies, test bed development, etc. Despite the apparent urgency for stop-gap transportation in large parts of Vietnam which generated the ARPA/Buships/Chrysler Marsh Screw Amphibian, its development cycle, from study through design, construction of test rigs, and ultimate rejection (by a committee), was little better. Study began in 1948, the first test rig appeared in December 1961, and stateside tests in relation to its designed function were only completed in October 1964 [Kraemer, 1965].

TABLE VI
DEVELOPMENT TIME FOR CURRENT MODEL VEHICLES

VEHICLE	PRELIMINARY STUDIES, ETC.	TEST ESTABLISHED	DEVELOPMENT CONTRACT LET	1ST PROTOTYPES DELIVERED	COMPLETE DEVELOPMENT PHASE	PRODUCTION CRUISED	1ST PRODUCTION DELIVERED
Model 3-1/2T 800	Early 55 (Same Gear) Oct 55 (NOVA Report)	June 55	Mar 55	Jan 56	June 56	Maybe 56 (?)	1st 7 (?)
Model 3-1/2T 800	Mar 56 (New MC'n)		Jul 57	Nov 56 Jan 57 Jan 57	??		
Model 3-1/2T 800	1957 (Studiot) 1958-59 (3 Test Models) Oct 59 (NOVA Report)	Oct 55	Mar 55		Sep 55	Dec 55	1st 5 (?)
Model 3-1/2T 800	May 56 (Staff Study) Apr 57 (NOVA Conference)	Apr 57	June 58 June 58 June 58	Aug 58		Sep 58 (?)	?
Model 3-1/2T 800	1958 (Pre-Test Test Run) 1957-58 (BAT)	Sep 58	Early 58	Aug 58	Feb 59	??	

Designed for weight reduction
Simplified for design
1957
1958

Not all peacetime developments have been quite as leisurely. Exploiting experience with prior LVT developments and the M73, the successful tracked M19 Armored Personnel Carrier proceeded from requirements to first delivery (1956) in just 66 months, and its still more successful successor, the M113, in approximately 48 months (1959). The German, Swedish, French, and Japanese have each since developed similar vehicles in about the same time span, although the British F.V. 432 APC took approximately five years from requirements to first delivery [Ogorkiewicz, 1964, 1966].

Even these respectable response times reflect cautious peacetime conditions, however. Some WWII experience may be cited briefly to indicate the other end of the scale. Just prior to U. S. entry into the war, but following a long period when military matters were far from foremost among U. S. problems, the span from receipt from the Armor Board of proposed military characteristics for what was to become the successful M-4 Medium Tank until production of 16 units per day was 21 months. Of this, some five months were spent in staff work prior to beginning actual design work. Toward the end of the war, the span from initiation of the request for what became the M15, 76mm. Gun Motor Carriage -- in its way as radical a vehicle as the M-4 was before it -- through production of 16 per day was only 13 months [APC, 1965]. British experience was similar. While it was nearly four years from the inception of the "Churchill" tank

to large numbers being in the hands of troops, the "Black Prince," its intended successor, had at the war ended proceeded from the first discussions regarding its possibilities through acceptance trials in just one year (Gibb, 1946).

Of particular interest from the viewpoint of present interest in improving mobility, is the WWII development history of the venerable M19C Hensel (Churchill, 1945). The entire project was undertaken on a "crash" basis outside the existing (and overburdened) Ordnance Corps channels by a separate agency, the Office of Scientific Research and Development, where "... a well conceived project could pass through the entire review procedure, become authorized, and actually get started in a week" (Bush, 1945). Project responsibility and authority were both highly centralized.

The stated requirement which led to the Hensel was (briefly) for a small, versatile, air transportable machine for use primarily, but not solely, in deep snow (Silverman, 1946). The basic idea was first put before technical people on 1 May 1942, and design began on 17 May. The first model (T-15) went into production in November 1942; the second, completely redesigned model (M-29) in August 1943; and the final amphibious version (M-29C) in May 1944 (OSRD, 1944).

The truly remarkable feature of this cycle is that it covered the development of a totally new machine for use in an extreme and hitherto largely unconsidered environment. Its first seven months spanned extensive testing (and rejection) of all vehicles then available having any snow-going

potential, and intensive practical research on the controlling features and properties of the terrain. The final product stands to this day, over twenty years later, as perhaps the most mobile off-road vehicle ever accepted into the ranks of standard Army vehicles, not only in snow, but in a wide range of other severe off-road conditions found all over the world. Thus, although originally conceived as a "special purpose vehicle," its outstanding mobility created for it a definite niche. By the war's end, 3300 M-15C's were produced (plus 3736 earlier models) and 18,000 more were on order. And this was despite numerous mechanical deficiencies and a definitely limited field life. The lesson, perhaps, is that while "mobility" cannot be sold on paper -- at least not yet -- it is welcomed in actual field conditions, even at "costs" which are considered unacceptable back at the home office.

As a final example of what is possible under high pressure and when, additionally, requirements are met insofar as practicable through the use of proven components and available technology, is the development, also under OSRD management, of the WWII DUKW, 2-1/2-ton 6x6 amphibious truck [Stephens, 1944, OSRD, 1946]. The concept, based upon conversion of the then standard Army "dodge-and-a-half," was first broached on 19 April 1942; the first pilot model was under test by 3 June 1942; the first production models were delivered 21 November 1942; and they were first used in quantity in the invasion of Sicily, 9 July 1943. By December 1943, 20 months from initial conception, production was at the rate of 1500 per month. Needless to say, there were not many aimless committee meetings in the interim.

The problem of response time is a serious one, well recognized in its time aspects at all levels of the Army, although its effects upon the ultimate suitability of the finished product do not appear to be so fully appreciated. A 1961 Army Regulation (AR 11-25) had as its objective the reduction of lead time from project initiation to first production roll-off to a maximum of four years, seemingly a modest enough goal in vehicle development in the light of some of the experience just outlined. Yet, some five years later, special organizational arrangements (JRATA, PROVOST) have been necessary to replace the "normal 5-10 year" lead time when dealing with requirements generated in Vietnam [Science, 8 April 1966].

Three factors distinguish the wartime and better peacetime efforts from the rest. The most obvious is a sense of urgency. But additionally, the more timely developments have been characterized by assignment of clear responsibility to identifiable, accessible individuals and manageable groups, and the divorcement of all tangential research and development from the operational line by which the requirements are met in production hardware.

While much of the present Hydra-headed staff work which screens, checks, and rechecks the work from beginning to end has the laudable purpose of reducing development time and, particularly, dollar losses, its real effect in relation to ground-crawling vehicles appears to be quite the opposite. Perhaps present circumstances will generate the sense of wartime urgency essential to rearrange procedures along the lines which have proven necessary in past situations where the problems were real and pressing.

The General Impact of Mobility Research Results
on Design

In many areas, weak ground crossing ability per se may be required only occasionally, but it is more frequently a major element in combined impedance systems. Recent enthusiasm for obstacle and ride studies and the mounting evidence that many other elements of design enter into the off-road performance of a vehicle [cf. Listen and Hennessey, 1966] have tended to downgrade the importance of soft ground mobility. Regardless of the frequency of occurrence of the problem, however, a good level of weak soil mobility remains one of the important "limiting hazards" of off-road operation [Radforth, 1964] with which a truly mobile machine must be able to cope, and hence a key consideration in its design. Life would be much simpler if this were not the case.

To improve soft-ground mobility, the nominal unit ground pressure of a given vehicle configuration must be reduced. This is not news, but the relationship is inescapably direct. Figure 6 shows the performance of a single tire in sand and in clay as functions of appropriate loading parameters [Freitag, 1945]. It is evident that for a given tire (b = tire width, d = tire diameter) at a given deflection ratio (δ), the tire's drawbar performance in a given soil (CI or G) decreases almost linearly as the nominal unit ground pressure (NUGP) increases, in either soil type. Performance is no more unaffected when an off-road vehicle goes overweight than when a boat or an airplane is overloaded.

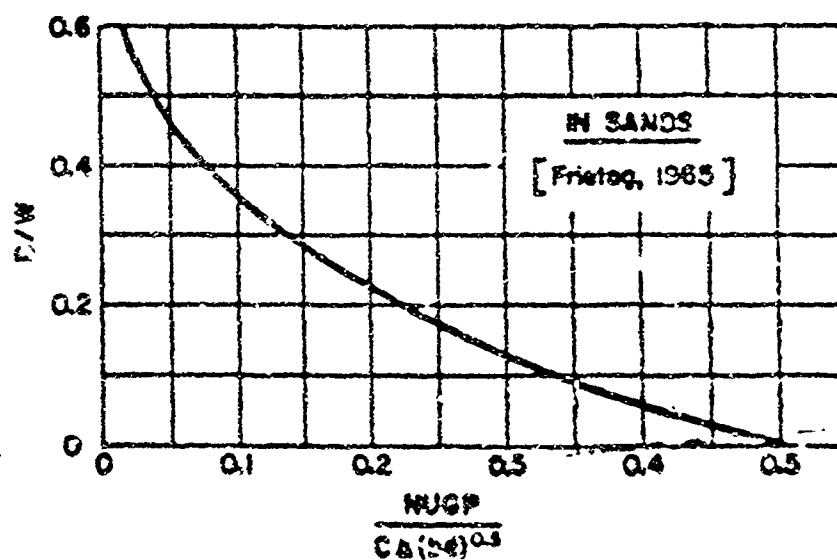
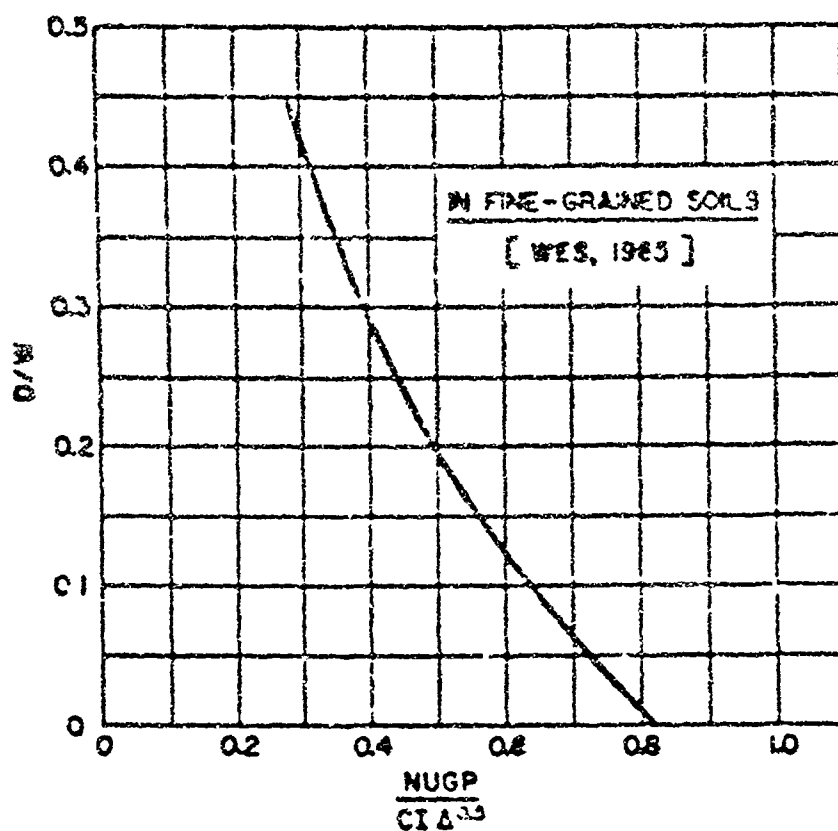


Fig. 6. Drawbar pull of a single tire

Secondly, soft-ground mobility is improved by taking whatever steps are practical to reduce the peak soil loadings under the vehicle. These include articulation of the running gear elements so that each unit can bear its approximate share of the load regardless of the convolutions of the surface; a long configuration to reduce load transfer effects on slopes; and reduction in stress increments due to steering; as well as improving the pressure distribution between gear (tire, track, what have you) and soil in the contact area per se.

To improve obstacle crossing ability, the machine needs a long effective wheelbase, for thrust, stability and bridging when necessary. The vehicle should be articulated in the pitch plane so that it may in effect hoist itself over an obstacle bit by bit, rather than all at once (with some part always in a position to maintain footing for control and traction as the others are scrambling over) and so as to avoid having a "trapping" dimension. If the articulation is controllable, or active, further gains are possible.

Obstacle avoidance is aided by agility, the ability of the driver-machine system to change direction rapidly and radically, and by keeping the vehicle narrow, its minimum turning radius small, and its swept width during a turn to a minimum. High speeds across rough terrain require a long wheelbase and a deep, soft suspension with adequate damping and roll stability, and are aided by reduced unsprung weights [cf. Lehr, 1944; Klumper, 1945; Little, 1946]. Provided they are coupled with still greater suspension depth for obstacle absorption, active suspension elements theoretically can provide still further speed increases [cf. ATAC, 1943].

All of these facts are well known. Means are available to make useful (but not necessarily the ultimate) engineering calculations in relation to each. And, within its sphere, design improvements in any one mechanical aspect of the sort indicated bring with them continuous improvements in the appropriate mobility aspect. There are no discontinuities in the change in design versus change in performance curves. They are smooth, monotonic, increasing, with no important anomalies, no remarkable points where big changes in performance come from small changes in levels of basic parameters.

While there are points where these mobility requirements are themselves in conflict and require compromise -- the large gear required for soft-ground operation versus the light gear required for high rough terrain speeds, and the length desirable for many features and the size required for low loadings versus agility for obstacle avoidance, for example -- they are, by and large, remarkably compatible. The compromises demanded are feasible, manageable.

Platform loading: Because of the overwhelming importance of nominal ground loading upon soft-ground performance, it is instructive to examine the platform loading of various types of current vehicles. Platform loading (W/A), defined as the gross weight of the vehicle divided by the product of its overall length and its overall width, obviously represents the minimum NDCP feasible in a given vehicle if its total platform area could be utilized for ground contact. Figure 7 gives approximate curves of (W/A) versus GVM for current practice in several vehicle types. Excepting the hovercrafts, the data from which the several curves are drawn are reasonably well fit by an equation of the form

$$W/A = K \left(\frac{GVM}{1000} \right)^{0.2}$$

Scatter is, of course, great. Values of "K" are as follows:

Military tracked vehicles and tanks	0.27
Armored cars	0.25
All-wheel drive military trucks	0.19
Articulated tracked vehicles (mostly commercial)	0.15
Commercial marsh buggies	0.12

And, misfitting the same curve to hovercrafts to permit a direct, if inexact, comparison,

Hovercraft $K \approx 0.05$

From these figures it is evident that, for a given gross vehicle weight, the difference in

The form of the equation implies that

$$GVM = L^3$$

(where L is a characteristic linear dimension), or that the density of the vehicle and load increases with vehicle size; i.e., more material -- machinery, structure, payload -- is packed into the envelope as the vehicle size becomes greater, than would occur if they were scaled up geometrically. Put another way, it suggests that the "void ratio" of the larger machine's loads to be lower than on smaller ones.

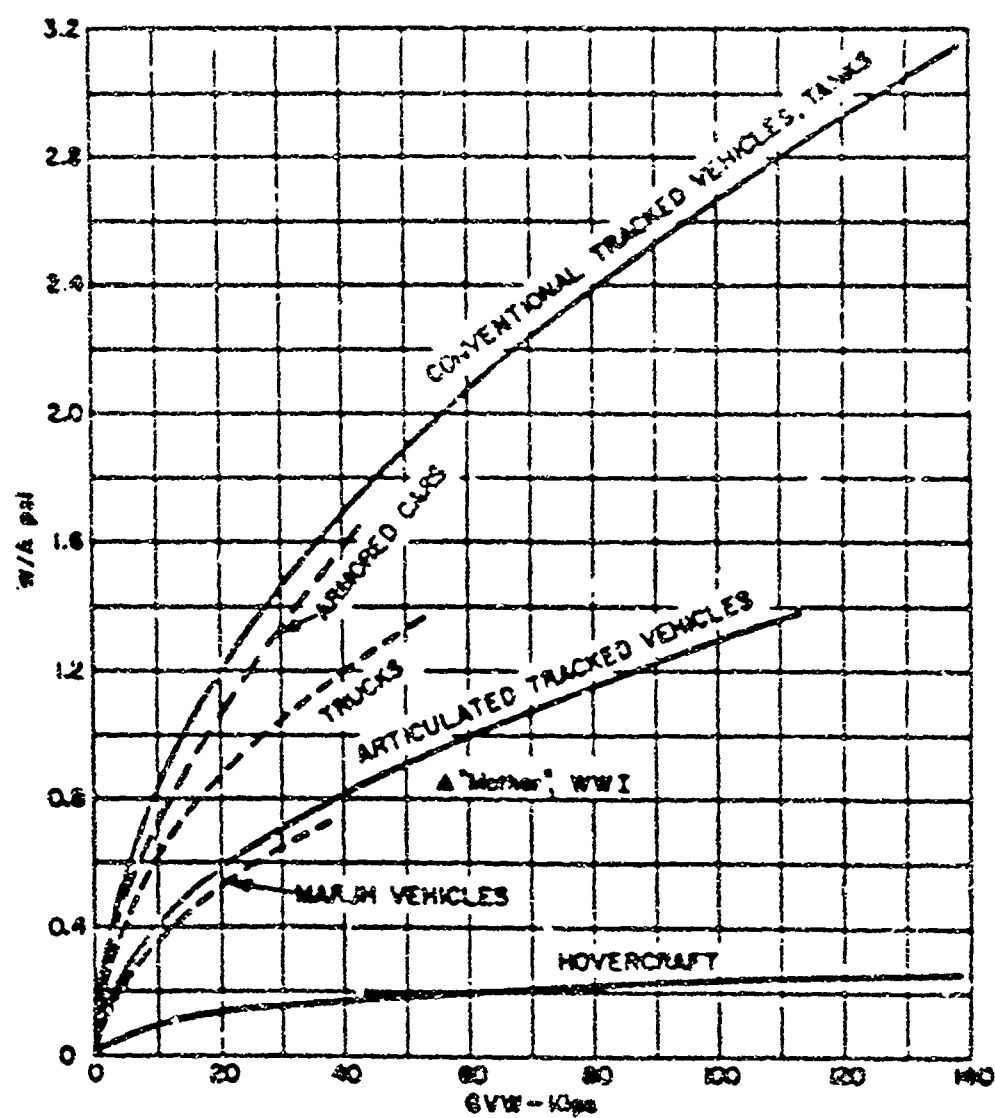


Fig. 7. Platform loadings of off-road vehicles

platform loading between a relatively conventional looking vehicle, and reasonably practical high mobility machines is of the order of only two. Put another way, the overall dimensions of the latter are essentially 40 percent larger for the same GTV. The figures also demonstrate that one current problem with hovercraft as off-road (or even on-road) vehicles of any reasonable load carrying capacity is clearly that their linear platform dimensions must be of the order of two to three times those of the familiar ground-crawlers they might replace.

Of course, on ground-crawlers, the entire platform area cannot in practice be utilized for nominal ground contact on firm surfaces (as used in computing MDCP). In fact, it has proven difficult in practical machines so to utilize more than one-half of this area, and on most conventional off-road vehicles it is far less. Rough figures for several classes of existing vehicle are as follows:

	<u>nominal contact area</u> <u>platform area</u>
Tanks and APC's	0.15-0.25
"Low Ground Pressure"	
tracked vehicles	
skidsteered	0.10-0.15
articulated	0.40-0.55
Off-road trucks	
4x4	0.07-0.10
6x6	0.08-0.12
8x6	0.10-0.12
Armored cars	0.04-0.10

The tracked vehicles examined included the small "Dollyless," articulated Rat [Stypinski, 1958], the 50-ton "Dollyless," articulated MUXI-01 [Nuttall and Thomson, 1960], and the successful Robin-Rodwell working tractors [Robin-Rodwell Mfg. Co., Ltd., 1964]. Thus, the upper values given pretty well represent maximum practical values for tracked vehicles. A practical upper utilization limit in wheeled vehicles, which has not before been approached, is represented by the VMEA 10x10 test bed on Terra-Tires, which manages to convert nearly 50 percent of its platform area to nominal contact area [VMEA, 1965].

The importance of these latter figures is underscored by the following approximate ranges in NUGP which have been indicated from accumulated experience and/or studies to be necessary to ensure adequate performance of tracked vehicles in a sampling of difficult, weak terrains:

Floating marsh	0.5-1.0 psi	[Nuttall et al., 1954]
Deep tree-line snows	2.5-3.0 psi	[Thomson and Wilton, 1954]
Glacial Arctic snows	2-5 psi	[Mellor, 1963]
Muskeg	1-3 psi	[Thomson, 1961]
Marshland	2.0-3.0 psi	[Guskov, 1963]
North German plains	3 psi	[Uffelman and Erns, 1965]

The lower figures generally apply to smaller vehicles (1-2T G.W); the higher figures to larger machines (20-50T G.W); reflecting a general pattern in most natural weak terrains of increasing strength of the surface material at a given spot with depth. This is a "scale effect" which

larger vehicles may explicit if, as is ordinarily the case, they can tolerate proportionately large sinkages.

The several rough figures given clearly demonstrate the not always appreciated fact that low-ground pressure vehicle of a given pattern must be physically larger than higher pressure vehicles for the same job. There are two alternatives, each offering in practice only limited relief. First, the pattern of the vehicle may be changed, as from a "standard" military style of tracked vehicle to a "low ground pressure" configuration (having much less room in the hull between the tracks for machinery, men, cargo, etc.), or from a wheeled to a tracked vehicle, etc. And second, the overall weight of the vehicle may be reduced, by reducing either its tare weight and/or its payload. (The latter may sometimes be possible if its payload is machinery -- a drill rig, a weapons system, etc. -- which can be specified functionally rather than simply as a dead load.)

The Weight Problem

Notwithstanding the limited extent to which, in actual practice, weight reduction can mitigate the basic situation, it is evident that every effort must be made to reduce vehicle (and, as possible, "payload") weight where feasible. This problem is clearly recognized by military vehicle specifiers and designers. In recent years a three-pronged approach has been taken: first, to engineer and develop lightweight components; second, to explore the weight reduction possibilities of new materials and construction methods in complete "idea" vehicles; and third, simply to specify lightweight vehicles.

The comparison work has been conducted within the context of automotive production costs of the order of \$1/lb of empty vehicle weight, contrasted to \$30-40/lb for helicopters [Rieger and Rubin, 1939], for example. As a result, modest weight savings only have often been achieved, and these usually at the expense of durability and reliability. The pendulum is swinging back at the present time. A new track developed for the M60 tank family, aimed at doubling the current track life of about 2500 miles, will add one ton (3 percent) to the GVW of the M60 [ATAC, 1965].

A relatively recent demonstration of the weight-saving possibilities of new construction methods and materials, and of careful detailed design, was provided by the XM21, 2-1/2-ton 8x3 "Honeybear" [Bischoff, 1961]. Bonded aluminum honeycomb was used as the basic material for its monocoque body-frame structure, and aluminum was widely used in the power train, suspension, and

running gear. Full advantage was also taken throughout of the cumulative effects of weight reductions, particularly in the design and selection of power train and running gear components. The result was that its curb weight was 60 percent less than that of the standard M14 or M155 2-1/2-ton 6x6, even though it incorporated swimming capabilities, and its nominal unit ground pressure at gross weight, on 7.59 x 10 tires, was 30 percent less. Still more recently a similar exercise has been reported in which magnesium was extensively used in the hull and cab of a swimming 6x4 test bed. The weight of these components was reduced to only 10 percent of the vehicle's curb weight (Drake, 1965), which is comparable to the relative structural weights of high speed aircraft (International Science and Technology, Nov 1965) and represents a considerable improvement over the 15 percent budgeted to the same items on the (fully amphibious) XM147E2 6x6 Superduck (1958). Despite incorporating a number of other experimental innovations, not all of which were consistent with minimum weight, this machine, too, weighed only about 40 percent as much as comparable standard machines.

Neither the Honeybear nor the magnesium test bed was put through the wringer of field service, which would undoubtedly result in some "beefing up," and neither was designed for the 100 percent or more overloads at which standard deuce-and-a-halves regularly work. Their weights are commendable, nonetheless.

While no vehicles of such remarkably light weight have entered the system, the increasing use of lightweight materials in military off-road

vehicles attests that these exercises are not completely in vain. By 1965, the use of aluminum in military motor vehicles had climbed to 25,000 tons per year. On the high-production M113 A7C and the amphibious LARC 5's and LARC 15's, approximately one-half the vehicle weight is aluminum [Automotive Industries, 1 Dec 1965].

The third approach does not present as favorable an aspect. The game of specifying a lightweight vehicle is not new. The original MC for a jeep, for example, called for a curb weight of 1300 pounds and a GVW of 1900 pounds, while the successful WWII machine out the other end of the pipe had a curb weight of 2170 pounds, a GVW of 2970 pounds. However, it has a particularly pernicious effect in the present context for if the running gear, power plant, frame, etc., are designed for an unrealistic target GVW, they will all wind up overloaded in the final machine.

In recent years, requests for proposals have encouraged this kind of bad design by specifying (or sometimes "desiring") low maximum curb weights (often payload-to-curb weight ratios of one) which were clearly outside present straightforward automotive technology (cf. RDPD 60-31, 1960; REPD 62-22, 1962). Those blunders who take such requirements seriously are forced to make radical, expensive, and/or apparently near-responsive proposals, while others get the work. When delivered weights exceed specifications by 30 percent, 60 percent, or more, with consequent overloading of the ground, the power train, etc., the contractor may be chided for "not facing up to his responsibilities in deciding upon the feasibility of technical proposals in his desire to obtain

contracts" [E. J. Fabini, quoted by Hieburg, 1966], but no one is fired and no one loses any money. But then, "despite being 35 percent overweight" -- GYS -- "tests at Fort Knox showed the DK32021" -- 8-ton 4x4 COER -- "was able to meet specified performance and mobility requirements" [AMC-TIR 10.3.1.3, 1964].

Weight-growth for several current vehicles, as reconstructed from published reports, is illustrated in Figure 8. Discussions of the problem with working vehicle engineers indicate that some part of the growth is attributable to the action of various committees which continually load on additional on-vehicle material, auxiliary equipment, etc., during the long course of development.

However, this appears to be only part of the story. The problem of unrealistic weight proposals is not peculiar to the Army off-road vehicle field, but is also found in Navy vehicles such as the LCA [cf. PR 529-338, 1959; Shipyards, 1964] and in the presumably weight conscious aircraft industry [cf. SAME, 1964], where careful parametric weight estimation has been shown to be accurate to approximately ± 4 percent [Marr, 1965]. The latest miscalculation is the F111B Navy version of the controversial TFX, which by mid-1966 was more than 20 percent over design maximum weight [Wall Street Journal, 3 Aug 1966]. Figure 9 shows other, earlier Navy aircraft experience as reported by Hook, who euphemistically comments ". . . some of our growth results from overly optimistic weight proposals submitted in an atmosphere of fierce competition. It may also be said that the desired characteristics called for

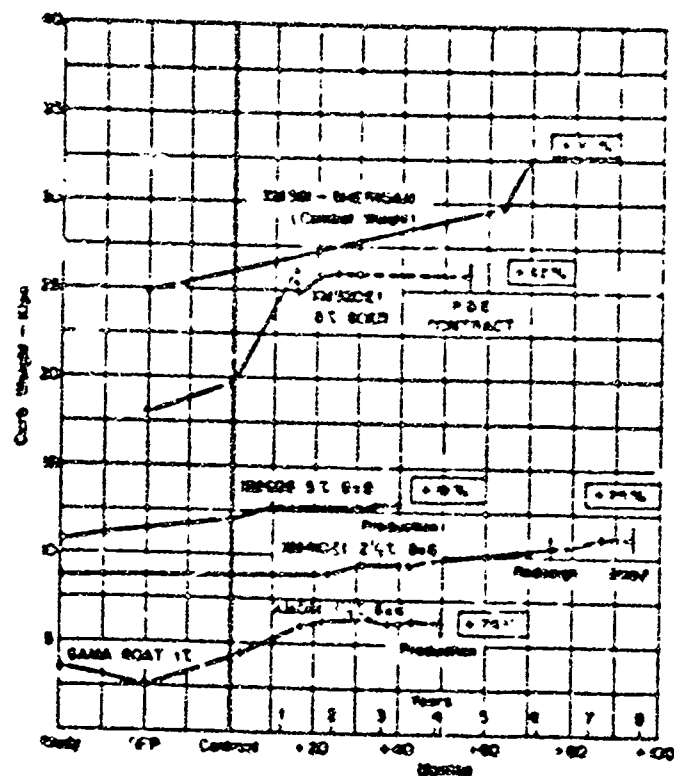


Fig. 8. Weight growth of recent experimental off-road vehicles

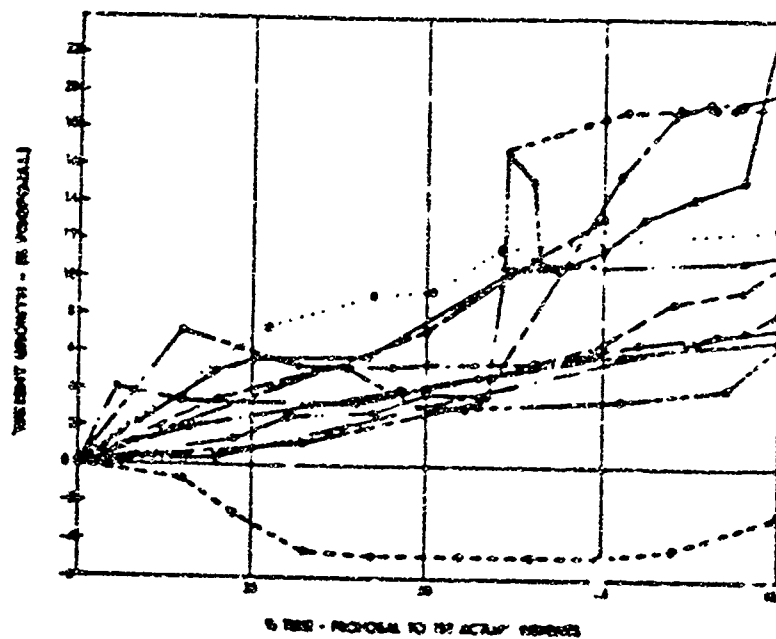


Fig. 9. Weight growth of naval aircraft

in the Type Specifications were unrealistic" [Hook, 1966]. Apparently, as in the military vehicle field, the bidder who suggests that the king is naked is a born loser.

Suffice to say that the problem is serious, particularly in relation to design for improved off-road performance. Its solution lies in developing clear lines of responsibility, in putting specifications in purely functional terms insofar as possible, and leaving the weight, dimensions, power, etc. (and sometimes cost), necessary to do the job up to the vehicle engineer, and in reducing opportunities for committees tinkering during the course of the engineering.

At a more detailed level, it will take better weight control engineering. This will cost additional money. The Navy weight control program for ships, instituted in 1961, is reported to cost 1/2 percent of the total cost of a ship [Kachtschels, 1965].

A viable weight control program for off-road vehicles must include development of multiparameter estimating procedures such as described for aircraft by Marr [1965]. Sound engineering and historical interrelationships must be developed between component weights, loads, speeds, dimensions, costs, etc. Rough estimating figures are used by everyone (3-4 lb/hp for gasoline engines, 1-3 lb/hp for gas turbines, etc.) but what is needed is more precision and an accounting for the cross influences. As an example of the latter, Artinian and Terry have shown that, in a fully rationalized automobile design, the addition

of one pound to the weight of its steering gear will add a further increment of more than 0.3 pound to other parts of the car [1961]. A beginning in relation to tanks was made by Neville Associates [1956], but much more is required.

The Weight and Cost of Mobility

It is often not realized that additional off-road mobility requirements will, at the present juncture, begin by adding to the tare weight of a vehicle for a given function. Consider basic tire weights, as an example.

Regression analysis of published data on the weight of a number of off-road tires for various services [Goodyear, 1966] leads to the following simple equation for the weight (W_t) of a single tire of more-or-less conventional form and construction:

$$W_t = K_1 \left(\frac{bd^2 W_1^{0.5}}{d_p} \right) + K_2 \quad (\text{lb.}) \quad (1)$$

where

W_1 = maximum rated load in pounds on the tire at its designed inflation pressure. If highway operation is included, the load (and, implicitly, the inflation pressure) for this service is used.

b = undeflected tire section width (in.)

d = undeflected tire outside diameter (in.)

d_p = rim diameter, in.

Values of K_1 and K_2 vary somewhat for various types of tires. Average values are tabulated below:

		K_1	K_2
Highway	Mileage Tread, standard	0.0015	10
	Duplex	0.0011	19
	Extra Small	0.0017	1
Off-Road	Grader	0.0014	20
	MDCC Military*	0.0013	0
	Sand	0.0009	20
	Earthmover	0.0011	190
	Rock Tread	0.0015	0
	Duplex, Rock Tread	0.0011	20
	Compactor (slow speed)	0.0011	0
Terra-Tires**	Smooth	0.0003	8
	Terragrip Tread	0.0006	10

*Cooling only: tubes and flaps add approximately 15.

The scatter of actual Terra-Tire weights versus values computed by this equation is relatively great, suggesting that the form of the equation is not entirely appropriate for these extreme types -- which is not surprising. The constants given provide rough guidance, nonetheless.

The degree of fit typical for the more-or-less standard tire types is illustrated in Figure 10, which compares actual versus computed weights for grader tires (medium directional chevron tread), sand tires, and the nondirectional cross-country tread military tires, each covering a wide range of loads and dimensions. While the suggested tire weight equation is undoubtedly inexact, tire building is itself an inexact science. Some of the points which appear to be bad in the correlation diagram are, on examination of the basic data, obviously out of line with other tires for nominally the same service, quite apart from this particular regression. Frequently they are tires for which there is relatively little call; usually they are heavier than calculated.

Those few tires which are substantially lighter than computed are generally the popular sizes and types in which there is considerable price competition. The weight -- and hence cost -- savings which can be made under this pressure are illustrated by recent government experience. It was reported in 1963 that over three successive purchases of the widely used 14.00x24 military tire to the identical specification, unit tire weights fell from 170 pounds to 170 pounds to 130 pounds, a total of 24 percent, apparently due

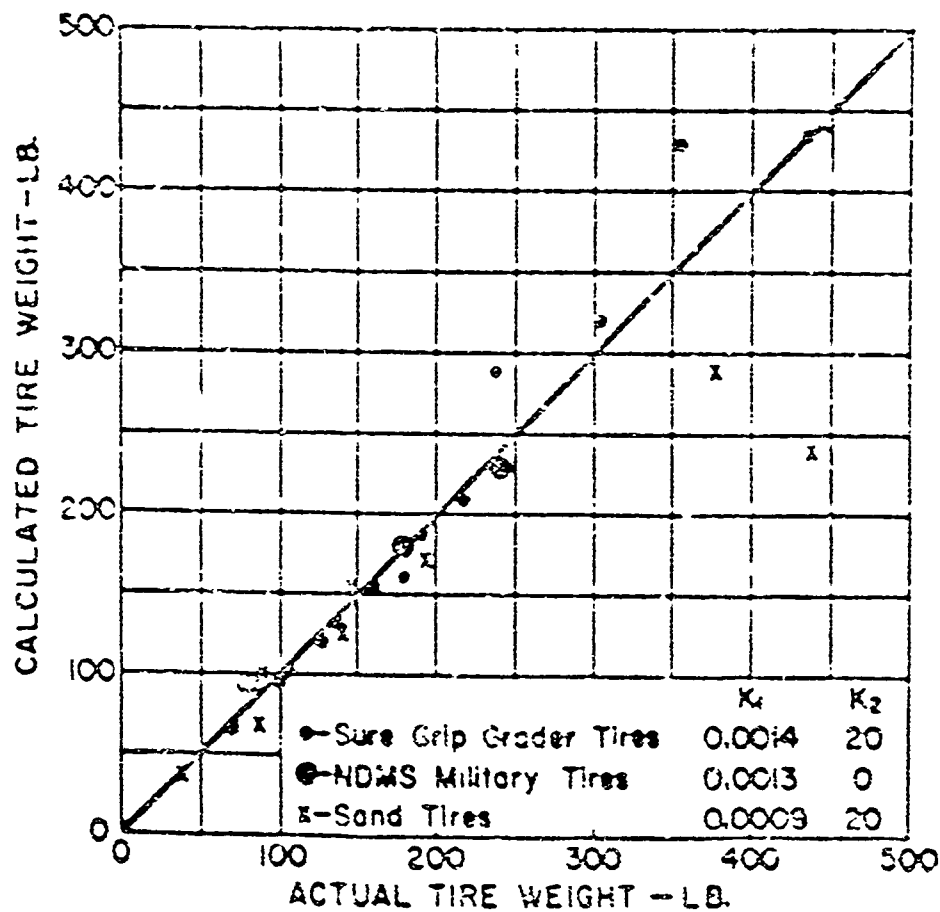


Fig. 10. Actual tire weights versus calculated $W_1 = K_1 \left(\frac{b d^2 W_1^{0.9}}{4} \right) + K_2$

primarily to reductions in under-tread rubber. Although the lighter tires proved difficult to recap, all versions performed satisfactorily on the vehicles.

NOTE: While the approximate equation above implicitly involves inflation pressure (I, psi) and tire construction (in terms of ply-rating -- PR -- for example), the specific relationship between these variables is also of interest:

$$PR = \frac{I}{f}$$

where $f = 25-40$, averages about 34.

It is reported that in current earthmover tire practice $f = 26$, indicating that a tire on the strong, stiff side is desired or required.

Neglecting the constant K_1 in the tire weight equation, which is relatively small for the size and type of tires of interest, equation (1) may be reshuffled to show tire weight as a fraction of total weight carried and as a function of nominal unit ground pressure (NUGP as defined earlier):

$$\frac{W_t}{W_1} = 2K_1 \left(\frac{d}{d_F} \right) \frac{W_1^{0.5}}{NUGP} \quad (2)$$

From this, two things are readily apparent. First, the weight of a tire to carry a given load increases proportionately as NUGP is decreased; and second, the relative weight of a tire to achieve a given ground pressure increases as the square root of the load to be carried by the tire. Weights of wheels and axles, of course, also increase with tire dimensions.

Finally, consider the effects, upon tire weight only (i.e., neglecting axle and power train trends, which may run counter), of the number (n) of tires used to carry a given total load (W). Substituting (W/n) for W_1 in equation (2):

*The weight of standard steel wheels on a pneumatic-tired military vehicle is generally less than 2 percent of GVW [Budd Co., 1958].

$$\frac{2W_t}{W} = 2K_1 \left(\frac{d}{j_r} \right) \frac{W^{0.1}}{MUGP} \cdot \frac{1}{n^{0.1}} \quad (3)$$

This indicates that the total weight of tires (only) to carry a given total load as a given *MUGP* decreases as the number of tires used (for which road axles) increases. Thus the weight of tires on a 4x4 would be 40 percent greater than that on an 8x8 of the same gross weight, and having the same *MUGP*. Conversely, the 8x8 might have a *MUGP* 40 percent less than the 4x4 for the same weight of tires.

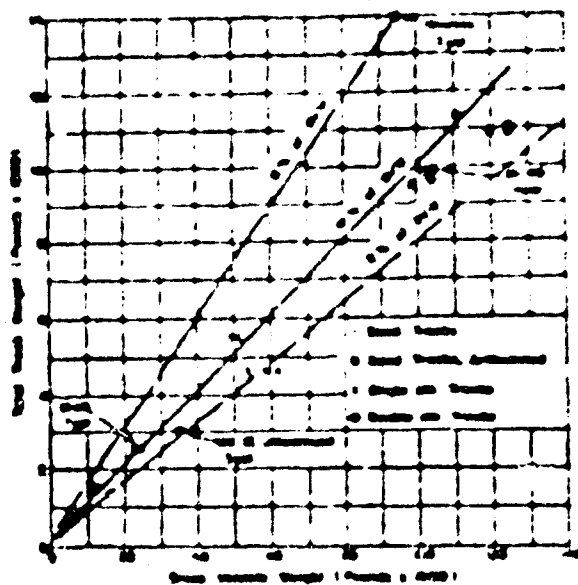
Some data on the weights of tracks [ATAC, 1965] and of aluminum road wheels for tracked vehicles [Faulkner, 1962] are plotted in Figure 11. Figure 11a shows that for a wide range of tracked vehicles, track weight alone runs from 8-15 per cent of gross vehicle weight. The higher figures are, not unexpectedly, associated with low ground pressure vehicles, ranging from the Weasel (2 psi, 5000 lb. GVW) to the MUSK-OX (3 psi, 100,000 lb. GVW).

Figure 11b presents the data in another form. The curve drawn illustrates the relationship

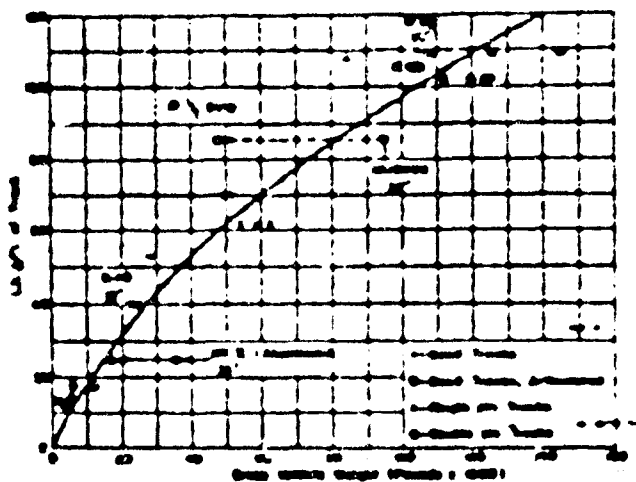
$$\frac{W_t}{L_t} = 0.04 (GVW)^{2/3}$$

(W_t/L_t = track weight per foot of length) which follows the trend of the data plotted, and is generally of the form which would be expected from geometric considerations. Tracks on four, low ground pressure articulated vehicles are included in the plot, and two, in an important sense, "beat the rule." However, experience has shown that track and suspension elements for properly designed two-unit articulated vehicles need be sized structurally according to the weight of a single

a. Total track weight versus gross vehicle weight



b. Weight per running foot



c. Total weight of road wheels

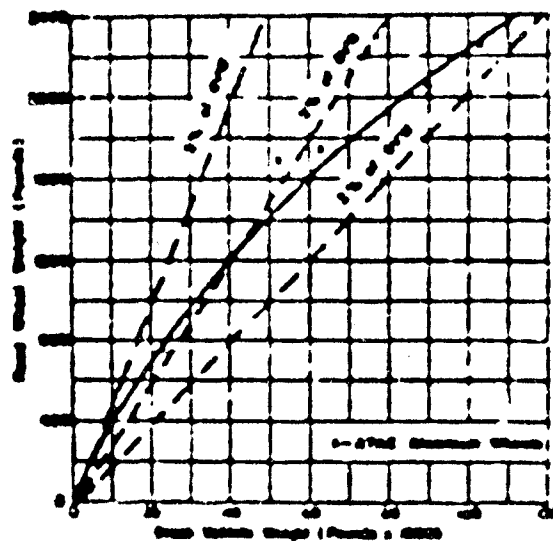


Fig. 11. Some rough track and suspension weight data

unit rather than the GVW of the complete vehicle (which is an advantage). When this is taken into consideration (as shown, by replotting the unit track weights of the articulated vehicles at one-half their GVW), it is evident that the low ground pressure tracks again tend to be heavier than normal width tracks. The only exception is the special duty 33-inch band track with forged aluminum grousers, used on the Mark II Pelecat [Materials in Design Engineering, May, 1961].

The overall effect upon tracked vehicle weight of increased soft-soil mobility requirements (in terms of NUGP) is suggested in Figure 12. This figure illustrates a tracked vehicle design relationship derived empirically from consideration of four conventional tracked, low ground pressure, floating cargo vehicles, the Vessel, the Otter, the M116, and the XM548E1. It shows a possible relationship between payload-to-curb weight ratio (P/W_c), payload, and NUGP. While this is simply a regression on historical data and, as a matter of fact, may or may not be true, it demonstrates the probable form of the relationship among these variables. If it is indeed accurate, it shows that specifying the "magic" value of $P/W_c = 1$ is particularly ridiculous for this class of machine at low payloads and low nominal unit ground pressures. Considerably more, and more detailed, more accurate relationships of this kind need to be developed to aid in understanding the interrelationships between desired features and to encourage realistic expectations.

The message is nonetheless clear. One of the intrinsic costs of increased mobility requirements is larger and heavier vehicles to carry a given

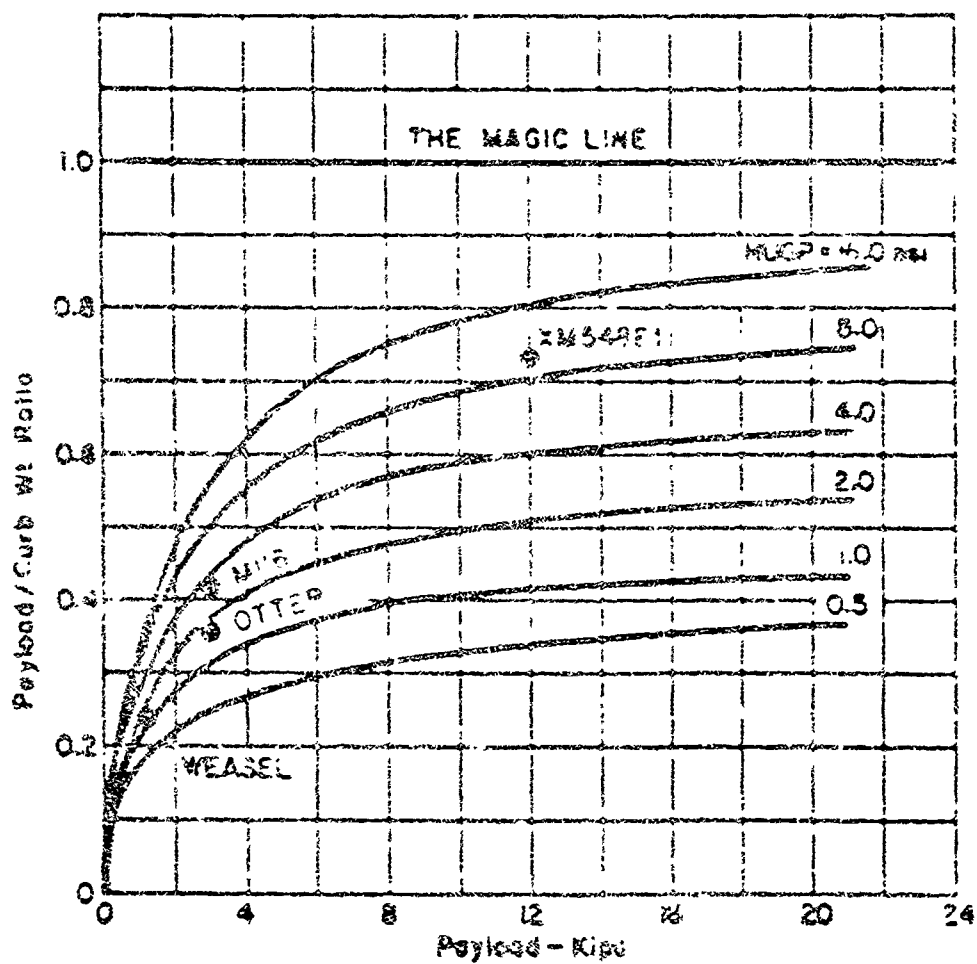


Fig. 12. Approximate payload curb weight ratio of existing tracked cargo carriers as influenced by MUCP and payload

lead. While this has been illustrated primarily in relation to soft-soil mobility, it is also true of other aspects. Increased speed in rough terrain requires increased wheel travel at least (usually a bigger machine in some respect) and increased running gear ruggedness (more weight and/or more cost for fancier design, better materials, etc.).

The additional weight per cc of more mobile vehicle configurations costs hard cash at purchase time -- \$1.00 to \$2.50 per pound (Jones and Lett, 1963; Ogorkiewicz, 1963, 64, 65). Current original equipment manufacturer prices for production off-highway tires range from about \$0.65 to \$1.00 per pound. The lowest prices are for popular, and hence competitive, types in the middle size range. More special cataloged tires may cost as much as \$1.25 per pound. (Federal taxes, a function of the amount of rubber in the tire, run about \$0.10 per pound of total tire weight.) Military tracks bought in quantity range from \$0.40 to \$0.80 per pound for link type tracks to \$2.00 to \$2.50 per pound for band type tracks as generally used on lower ground pressure vehicles. And, of course, the direct increase in running gear weights and costs is only the beginning.

As an example of the total impact, consider two otherwise comparable tracked vehicles (with swimming ability), each to carry a 5-ton payload, one at 10 psi AGP, the other at 1 psi. Making the large assumption that the curves of Figure 12 are basically valid, the first vehicle would weigh 14,000 pounds, the second 24,000 pounds. As a first estimate, the cost of the ultra-low ground pressure machine would accordingly be 70 percent greater than the higher ground pressure vehicle.

The alternative of going to aircraft type of design, materials, processes, and quality control cannot be seriously considered. Even assuming that such an approach would reduce the tare weight of the 5-ton payload low ground pressure vehicle to 5 tons (the "magic" ratio of payload/curb weight ratio of one), the cost per pound (at aircraft prices) would rise by a factor of 10 or more, resulting in a net increase in vehicle first-cost by a factor of at least 4. Even the relatively modest increase in per pound cost of the XM561 1-1/4-ton 6x6 (by ATAC out of Gama Goat) over figures for such high production items as the standard 2-1/2-ton 6x6 truck, is causing some consternation [Watson, 1966] despite its performance [Borris, 1965], and cheaper alternatives such as the XM705 nonswimming 4x4 are already under study [Morrison, 1965].

Reliability and Maintenance

Competing most strenuously in the design compromise arena with the dictates of off-road performance are the requirements for reliability and maintainability. The competition is on three levels: weight and space, dollar cost, and lead time. Reliability is, of course, a prime factor in any consideration of vehicle effectiveness. A vehicle which cannot move because of a mechanical failure is fully as immobilized as one which cannot go because it is up to its ignition switch in mud, perhaps more so. For this reason, there has from time to time been a tendency to lump reliability and mobility, and many development projects in the past, justified on the basis of their potential contribution to "mobility," were in fact concerned with reliability, particularly on odd years when "mobility" has been the temporary key to the cashbox.

There is no question but that the reliability and maintainability of military equipment is a problem of overwhelming importance. Just prior to the buildup in Vietnam, one-third of the defense budget was chargeable to maintenance [Teal, 1965]. In the reliability-minded world of aircraft, nearly one-half of all peacetime aircraft losses (in or out of the services) involve equipment failures. Losses of naval aircraft from 1958-1963 killed trained operating personnel numbering approximately 10 percent of the output of the service schools

in the same period. And maintenance costs on the aircraft over the same 5-year period were ten times their original acquisition cost [Coutinho, 1964].

Army vehicle maintenance costs are relatively less than departmentwide or aircraft figures such as these, but this probably reflects, in part at least, the much lower relative peacetime utilization which is made of the more expensive vehicles such as tanks, which worldwide accumulate something of the order of only 100 miles or 10 hours of operation per month. They are nonetheless formidable. Direct parts replacement costs alone for the well-developed M60 Battle Tank, for example, are of the order of \$3.75/mile, of which, incidentally, over \$2.00/mile is for track replacement only. If the M60 tanks were operated only the 50 hours per month for which Army helicopters were reported 70 per cent available three years ago [Congressional Record, 6 Nov 1963], direct parts costs per year would be about 1. percent of first cost, and total maintenance costs, including personnel, shipping, shop costs, etc., would be perhaps 40 percent of the first cost per year. This is below quoted aircraft and avionics levels, but does approach their remarkable ball park.

In 1962, new targets for the reliability and maintainability of (then) future Army wheeled tactical and tracked vehicles were established [MIL-STD-1228, 1962]. In essence these called for the following, which are compared to contemporary experience in efficient, commercial, on-road fleet operations [Fleet Owner, Oct 1963].

	<u>Major over-</u> <u>haul interval</u>	<u>Maintenance</u> <u>man-hours per</u> <u>hour of operation</u>
Military (1962 target)		
Wheeled	25,000 mi.	0.07
Tracked	5,000 mi.	0.20
Commercial (1963 experience)		
Long-haul buses and trucks	150,000 mi.	0.40

(Overall commercial maintenance costs for these same vehicles were 5-8¢ per mile.)

Differences in overhaul periods are in part due to off-road operation, part to the military environment. Differences in maintenance manhours appear unrealistic. Maintenance costs of properly designed off-road trucks operating in Arabia were reported by Kerr to be twice those for comparable on-road equipment and operations [1956]. Overall operating costs of commercial buses and trucks in Africa have been reported to more than double when operations were on unimproved earth roads rather than good surfaced roads [Willard and Bonney, 1960].

At the 1965 American Ordnance Association meeting at Rock Island Arsenal, it was reported that sufficient progress has been made on the durability program that new targets for overhaul intervals were under consideration.

The approach taken to improve maintainability has been on a broad front. Frequency of preventive maintenance has been reduced, both by better design and by rethinking earlier procedures. Self-checking features have been designed into new components, system check-out analyzers have been developed, and use of unit replacement or plug-in module design has been stepped up. On the

organizational side, maintenance manpower and talent have been reorganized for greater effectiveness, "readiness indices" have been developed which, as one function, serve to check regularly on the maintenance effectiveness of individual operating units, and more efficient parts record keeping (TAEPS) and maintenance management analysis procedures (TAMMS) have been set up. Finally, a design training program has been put in operation which aims at starting maintenance improvement at the drawing board [Breakfield, 1965].

The Army durability-reliability-maintenance program has been plagued by the same sort of basic difficulties with quantification and lack of testable specifications as have beset the search for improved mobility. Moreover, the drive for improvement has been concurrent with pressures for new, lighter, more complex and less expensive machines and components. In 1963, two Army Regulations were issued to begin the quantification process in which the probabilistic nature of both problems was clearly recognized. Reliability was defined as the probability that materiel and equipment will perform their intended function for a specified period under stated conditions [AR 705-25, 1963]; maintainability, as the probability that required maintenance will be accomplished within a specified maintenance environment [AR 705-26, 1963]. Both features are to be specified in terms of minimum acceptable levels "quantitatively expressed with respect to environment and mission conditions." In each case a test plan is called for, to be a part of each new development, setting forth test specifications, ground rules, and statistical methods to be used in evaluating test results in relation to the specifications.

At the weight and space level, and the cost level, the competition between mobility and reliability and maintenance requirements is, for the most part evident. For improved mobility, all components should be light, often small. On the other hand, the easiest way to improve their reliability is generally to "beef them up." Alternatively, light weight and reliability may be achieved to some extent together if design, materials, processes and quality control, and costs are raised to aircraft levels. In other cases, mobility features may indicate the desirability of some increased complexity, such as suspension elements whose characteristics may be adjusted while under way [ATAC, 1965], variable track geometry [Stewart, 1955], locking differentials [Ansdaile, 1963], central tire inflation control [Stephens, 1944; Ageikan, 1960], etc. In every case, there is conflict not only with reliability and maintainability, but with weight and space as well, and, as always, cost. It is interesting to speculate on how mobile modern aircraft would have been if the aircraft industry had refused to give up the biplane, retract landing gear, or use wing flaps, because these steps were (each in its time) complicated and costly.

On a slightly subtler but perhaps more important level, the quest for reliability has a profound effect upon the rate of progress towards greater mobility. A complete operating vehicle is a system of components. In order to achieve reliability in the vehicle, each of its components must be reliable. In fact, each of its major components must be significantly more reliable than the level

of reliability desired of the whole. Off-road military vehicles are not simply draftees from commerce, with a coat of o.d. paint, however much the resemblance may seem in some instances [Bischoff, 1965], and most of their components are necessarily special in many ways. The more important components -- engine, steering transmission, track, etc. -- may be quite unlike anything available in civilian commerce.

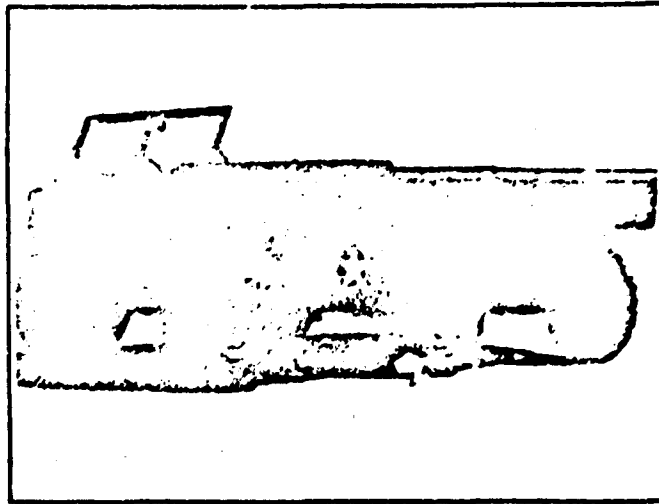
Accordingly, progress in vehicle development must be preceded by the development of suitable, reliable components. This relationship is strong. Lynde has pointed out that it is generally possible to predict the main characteristics of vehicles four to six years in the future from a look at current component developments [1959]. While U. S. Army component work is largely carried out without reference to a specific detailed vehicle design, it tends to reflect the status quo in vehicle morphology, and hence tends to impose that morphology upon vehicles yet unborn.

In relation to major improvements in ground mobility, which will require major morphological changes, such component development can actually be a drawback. It tends to force a choice between a vehicle changed only modestly in the directions needed, but made up of well developed components, and another of a proper, radically different form, but loaded with necessarily new and untried components. Not long ago this dilemma was theoretical only. However, in recent months there

has been a discernible disenchantment with such modest innovations as the XM410E1 and the Gamma Cost inspired XM561, in part because of potential and/or actual unsolved reliability and maintainability problems* which are in turn traceable in some measure to their having leapfrogged the components program to some extent.

*Also in part because of cost and because, due to poor translation of the original attractiveness concepts [Jankowski, 1963], to weight increases, etc. [AMC TIR 11-1-2819, 1963], performance does not come up to expectations.

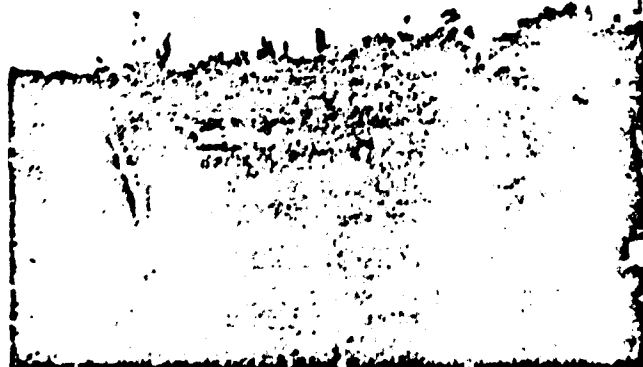
Gama Goat, 1959



XM561, 1964



M37 with Terra-Tires, 1966



wheels vs. Tracks

Despite the many ingenious devices which have been proposed through the years, including all the recent work on moon vehicles, design of a practical, working, ground-crawling machine early resolves itself into the selection of wheels or tracks of some sort for its running gear. The question of wheels versus tracks is a perennial exercise. There is no general answer; each situation must be considered separately. Unfortunately in the present military design system, the design choice is frequently made directly in the vehicle specifications, prior to a proper detailed performance analysis.

There is general agreement that the principal reason for using tracks instead of wheels is to obtain improved cross-country performance, primarily in operations in weak, fine grained soils, and secondarily for obstacle negotiation [cf. Adams, 1958; Lucas, 1961; Freitag and Janosi, 1963; Uffelmann, 1963; Swamp Fox II, 1964; Little, 1964; Depkin, 1964]. It is also generally known that tracks are more expensive to buy, to operate, and to maintain than tires, and that tracked vehicles are more troublesome on the road.

Where a vehicle's off-road operations will be largely in sandy soils, as in oil field work in Arabia and Libya, the job can be done on low pressure tires and, unless combat considerations dictate otherwise, is best done on tires [Kerr, 1950, 1955, 1956]. On the other hand, tracks appear necessary for flexible operation in snow terrains [cf. Kennedy, 1965] and desirable where slippery soils and slopes conjoin [Swamp Fox II, 1964], and are universally used on the heavier

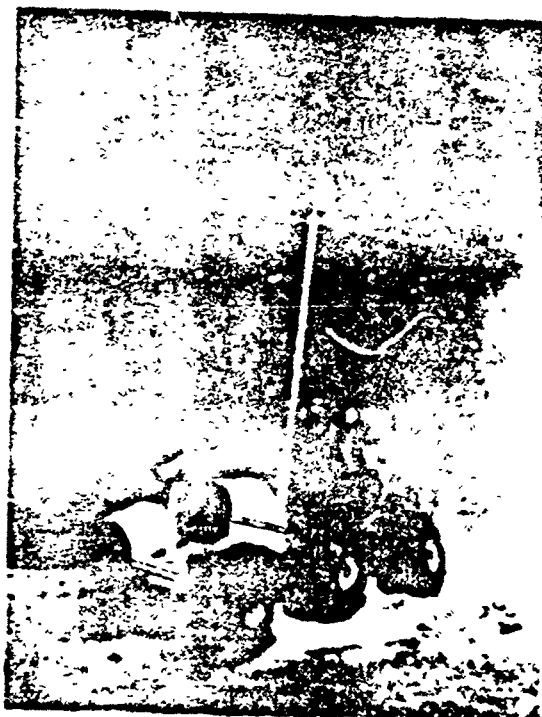
gun carriers such as tanks and self-propelled artillery because they can achieve a good level of cross-country performance in a configuration which is more compact and less vulnerable to gunfire than a wheeled machine of equivalent performance. The Europeans have developed a number of successful armored cars in lighter weight classes which have reasonable off-road mobility except in weak soils [Ogorkiewicz, 1965]. U. S. military emphasis for comparable combat vehicles, on the other hand, has been upon tracked vehicles such as the M113. Despite the current panic to obtain armored cars for use in Vietnam [cf. *Armor*, Jan-Feb 1966] -- essentially for road patrol work -- they are not considered suitable for general combat use over there [cf. Battreall, 1966; Moore, 1966].

Over the years, attempts have been made to reconcile the off-road advantages of tracked vehicles in extreme conditions with the on-road efficiency and reliability of wheeled vehicles through the combination of the two on a single vehicle in some convertible fashion [cf. the Lefebvre tractor described by Legros, 1919]. Despite the fact that Christie is revered for his introduction of large-wheeled track suspensions [cf. Carlisle, 1964; Ciccarelli, 1965], what he was in fact trying to sell to the U. S. Army was a vehicle whose important feature was that it could operate as a tracked vehicle off-road and, with the tracks quickly removed, as a wheeled vehicle on-road. Army interest was initially great -- WWI tracks had a life of only 90 miles or so -- but eventually foundered upon mechanical difficulties of track life and track installation time which Christie never satisfactorily solved [OCM Item 7522, 1929].

MOON VEHICLES

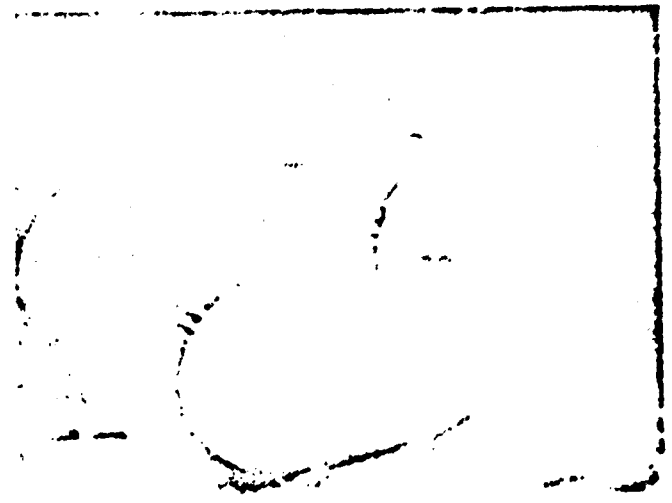


General Motors 1966

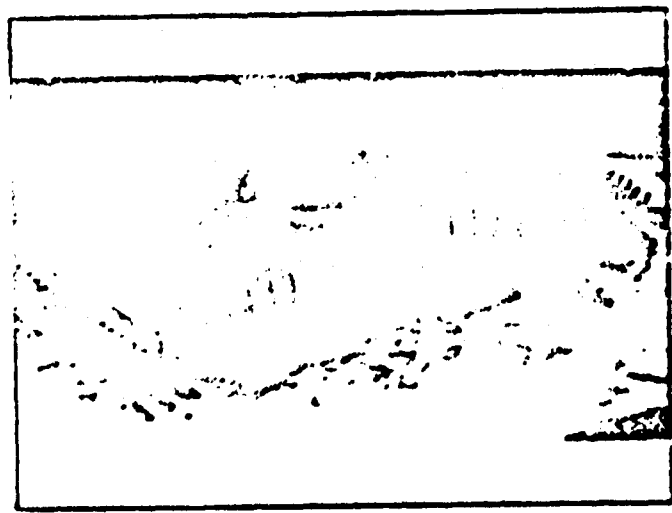


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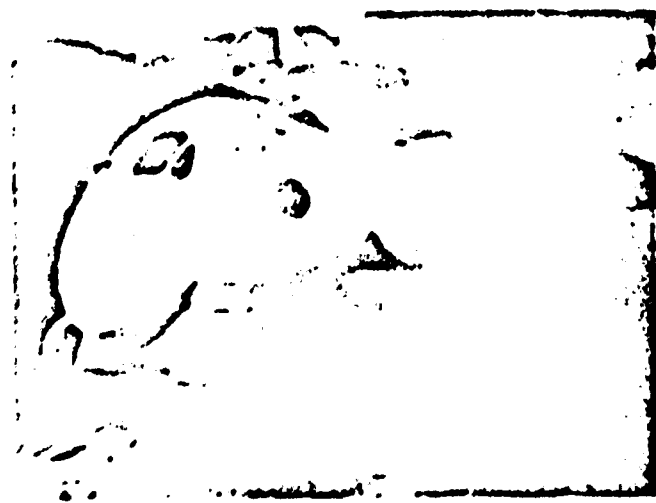
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General Motors



Northrop



Other attempts at wheel/track hybrids, beginning in the 1920's, utilized, on light vehicles, retractable wheels which stowed during off-road operation within the track envelope [cf. Heisl, 1926, 1927; Haecker, et al., 1935]. The most recent machine on this pattern is the Swiss JMG-20, a small 3-ton scout machine [Garnier, 1965]. Still another approach to hybridization is represented by the half-track vehicles of WWII [TM 9-2800, 1943].

Perhaps the principal, but not generally recognized, reason why tracks are generally considered better for soft-ground operation is that they can better utilize the vehicle's planform area to develop effective ground contact. As noted earlier, ordinary tracked vehicles convert 15-30 percent of their planform area into nominal ground contact area; whereas conventional off-road vehicles on tires (the vehicles which everyone thinks of when they speak of "wheeled vehicles," which fit automotive production facilities, and on which cost and reliability experience is based) convert only 8-12 percent of their planform area to effective ground contact area.

Experience and studies have shown that this two-to-one advantage tends to hold even in more extreme low ground pressure vehicle configurations. A number of tracked machines (mostly articulated) have demonstrated that 50 percent or more of the planform area may, in practice, be made available for ground contact on tracked vehicles, whereas the practical maximum on wheeled machines is perhaps 25 percent. Thus, despite the fact that trafficability studies seem to indicate that for equal "50, 27-30" performance in fine grained soils, the NUGP of wheeled vehicles may be 0.5-1

not more than that of a comparable tracked vehicle (see Appendix III), tracked vehicles maintain a considerable potential edge.

Moreover, experience shows further that wheeled and tracked vehicles of the same basic NUCP, in the range of 3 to 8 psi where they overlap in practice, will weigh about the same for the same job. The crude weight analyses which have been made herein for illustrative purposes indicate that, insofar as track-only versus tire-only weights are concerned, the weight trade-off line may be approximately as shown in Figure 13. While such a curve, to be truly useful, should include many more components, it supports the general concept that to achieve low unit ground pressures, heavier vehicles should be on tracks, and that vehicles of extremely low ground pressure should also be on tracks.

An example of a successful, heavy, low ground pressure vehicle is the MUSK-OX, which has a GVW of 50 tons and a NUCP of only 3 psi (Nuttall and Thomson, 1960). This vehicle is 43 feet long, 10 feet wide, and 10 feet high, and carries 20-30 tons of payload on a deck less than 5 feet above the ground. Rough calculations indicate that to achieve approximately the same soft-soil performance, a vehicle on pneumatic tires would have to be 60 feet long, 13 feet wide, and perhaps 15 feet high. Its cargo would ride perhaps 7 feet in the air.

Practical examples of wheels-versus-tracks in the extremely low ground pressure range are the marsh buggies used for oil exploration work in Louisiana. Ten to twenty years ago, large wheeled machines were used, of which the most sophisticated

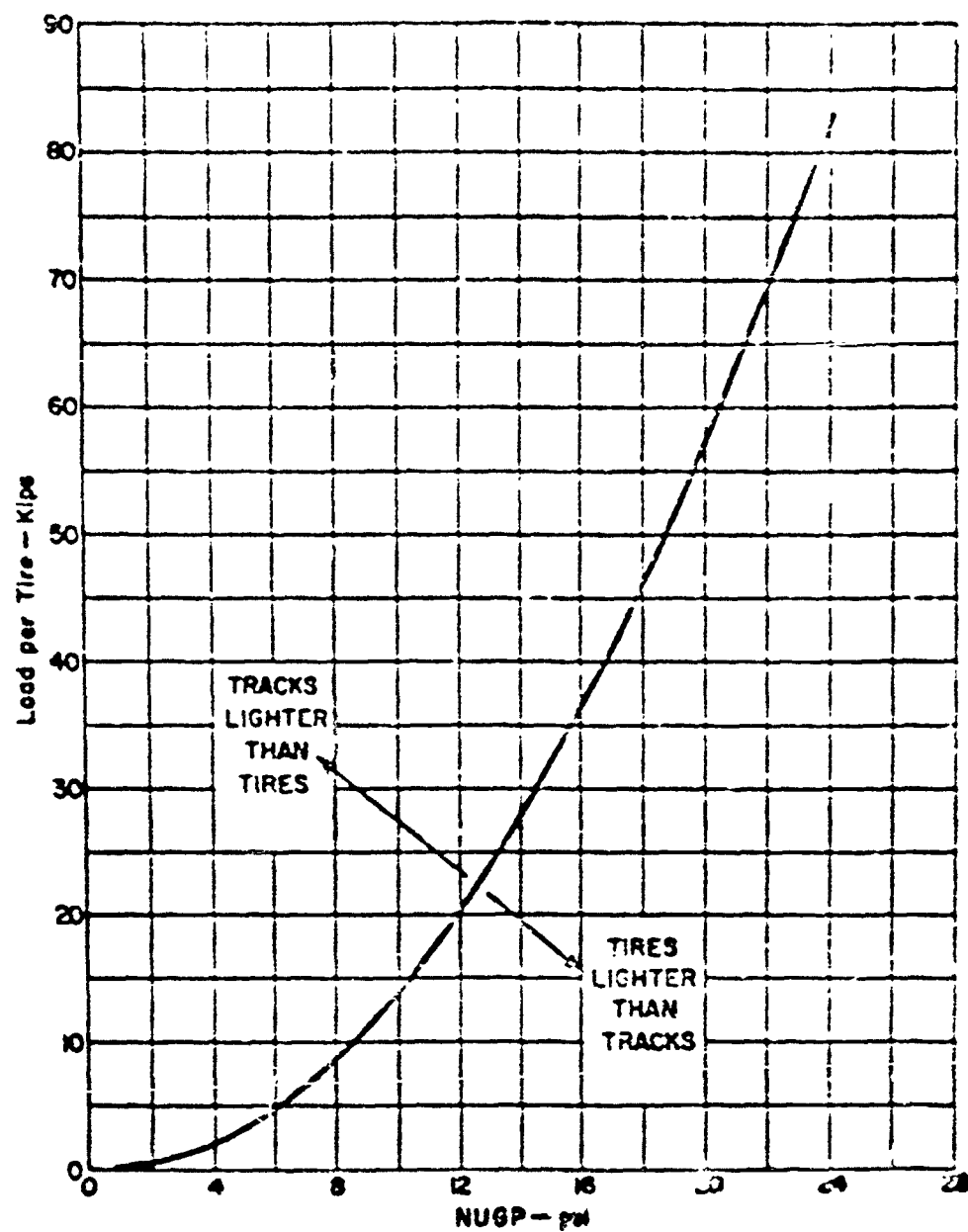


Fig. 13. Track versus tire weights

was the Gulf Marsh Buggy on 10-foot pneumatic tires [Jacobson, 1945; Nuttall et al., 1954]. Over the past ten years the wheeled vehicles have all but disappeared in favor of ponton tracked machines [Reynolds, 1951; Quality Marsh Equipment Co., 1964]. Both styles are in a sense monstrosities, but the tracked vehicle has won out despite its mechanical drawbacks essentially because it provides better performance in the problem terrain within a more compact and manageable dimensional envelope.

The normal, rigid frame, tracked vehicle has considerably more vertical obstacle capability than the ordinary off-road vehicle on tires. This is in part due to differences in configuration which could be resolved to favor better obstacle performance in the wheeled machine; in part to the higher traction usually available on the tracked vehicle because of its normally lower NUGP and more aggressive ground engaging elements. However, the discontinuity of ground contact on a wheeled vehicle is an unavoidable drawback in any event, and the wheel diameter required on a conventional vehicle to provide the step-height capability of any good tracked vehicle ordinarily would be prohibitive in conventional layouts.

Both wheeled and tracked vehicles are greatly improved in their obstacle-crossing and climbing capability by frame articulation which allows motion between the units in the vertical plane, as on the wheeled Gama Goat or the tracked MUSK-OX. The extremes of what may be accomplished through this type of articulation are illustrated by the 100-pound, 6x6, flexible frame, unmanned lunar vehicle conceived by Bekker for NASA [Bekker, 1963; Lee, 1966].

The ride of tracked vehicles in rough terrain -- and hence their operating speeds -- is generally better than that of normal off-road wheeled vehicles, largely because of superior road wheel suspension and the usual provision of a larger number of wheels in contact with the ground. This advantage is not intrinsic. However, it proves to be easier mechanically to provide a suspension to a large number of undriven wheels, as on a tracked vehicle, than to an equal number of driven wheels, as for example on an 8x8. On the other hand, track noise tends to degrade the ride of tracked vehicles; and in their conventional stubby form, their limited wheelbase makes them prone to high amplitude pitching. As already noted, the latter problem is significantly reduced through vehicle articulation.

There is a trend on off-road vehicles on large tires, such as the GCER's and the amphibious 4x4 LARCs [USMC, 1964], toward elimination of the suspension altogether, which further enhances the relative tracked vehicle ride advantage. Despite the cushioning effect of the tires, elimination of all other suspension results in a very poor ride in rough terrain. When the rigid axle design is coupled with a very short wheelbase, as on the Canadian timber-working vehicles, the off-road ride can be incredibly bad. Even on the road, speeds of large-tired, unsuspended 4x4's are limited to about 30 mph by resonant bouncing on their tires.

Conventional tracked vehicles are skid steered, which imposes distinct limitations upon their overall proportions and in some cases a practical lower limit to MUCP. A simple example of some of the detailed relationships which exist is shown in

Figures 14 (a, b, and c). Consider a conventional tracked vehicle with a gross weight of 100,000 pounds. Even if a maximum width of 12 feet can be accepted, the selection of dimensions for the track is already limited to the area shown in Figure 14a. Skid-steering considerations dictate that the length-to-tread ratio (L/T) should lie between 1.2 and 1.8 [cf. Steeds, 1943, 1950]. Current military practice favors a value between 1.4 and 1.6. Bridge crossing limitations dictate that the length of track on the ground should not be less than 124 inches, and, out of consideration for the pavement, on-road nominal unit ground pressure should be limited to 12.5 psi [ATC, 1962]. It is clear that the two primary considerations, gross weight and maximum width, through their interrelations with others, specified and not, have combined to limit severely the designer's freedom of choice in the shape of the vehicle. It is also clear that had it been specified that the maximum NUGP should be 5 psi, this would have fallen outside the feasibility "window."

Figure 14b shows how the window would diminish if the maximum width were reduced to 10 feet. In this case, minimum feasible NUGP would be 8 psi. Figure 14c illustrates the effects of reducing the gross vehicle weight while holding the maximum width to 10 feet. Figure 15 summarizes the feasibility windows for conventional tracked vehicles in terms of overall width required for any GVW to achieve 2 psi or 12.5 psi NUGP with L/T ratios of 1.2 and 1.8.

Skid steering is also occasionally used on wheeled vehicles, as on the small Canadian 6x6 Jiger [Bischoff, 1964; ATAC, 1964], the unsucces-

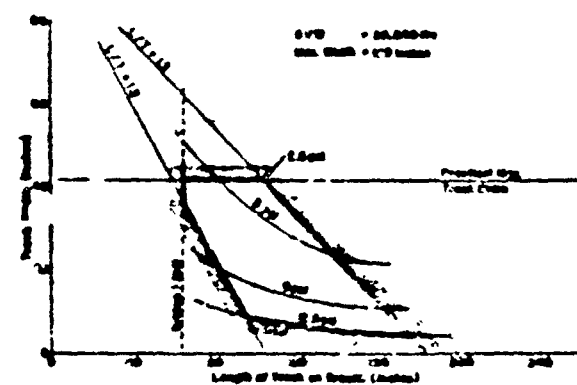
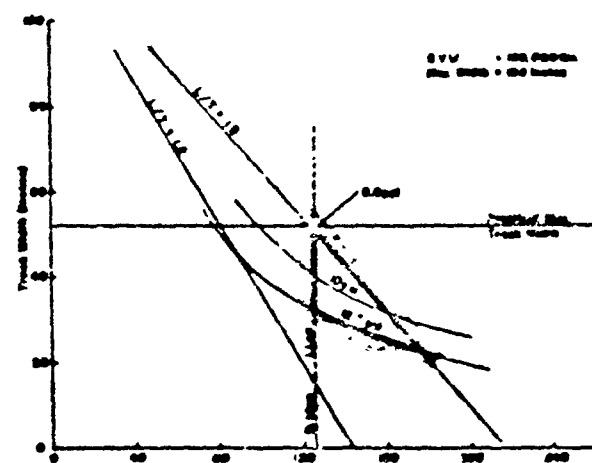
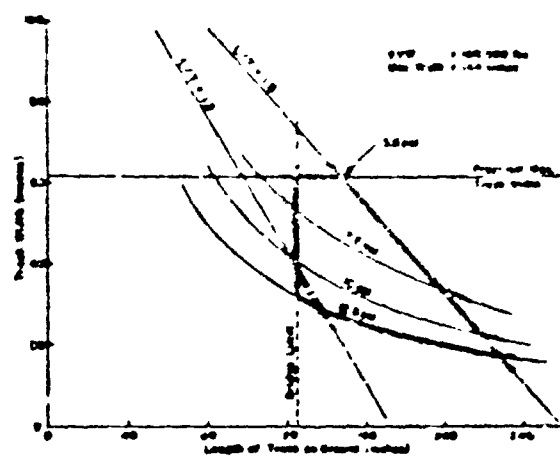


Fig. 14. Skid-steered tracked vehicle design "windows"

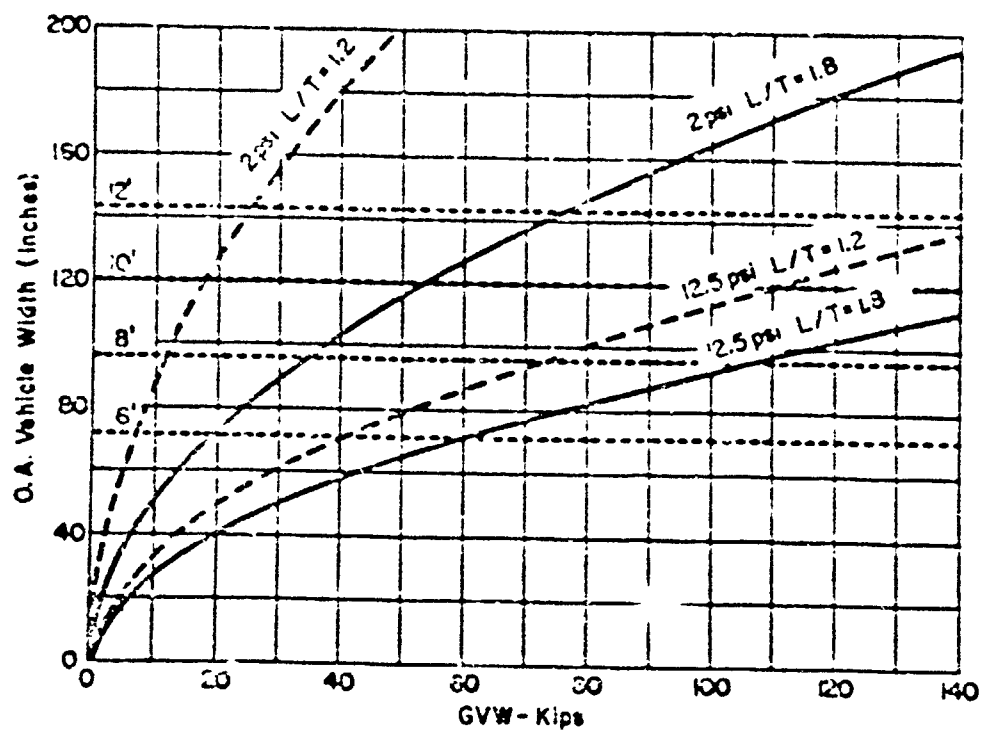


Fig. 15. Skid-steered tracked vehicle geometry

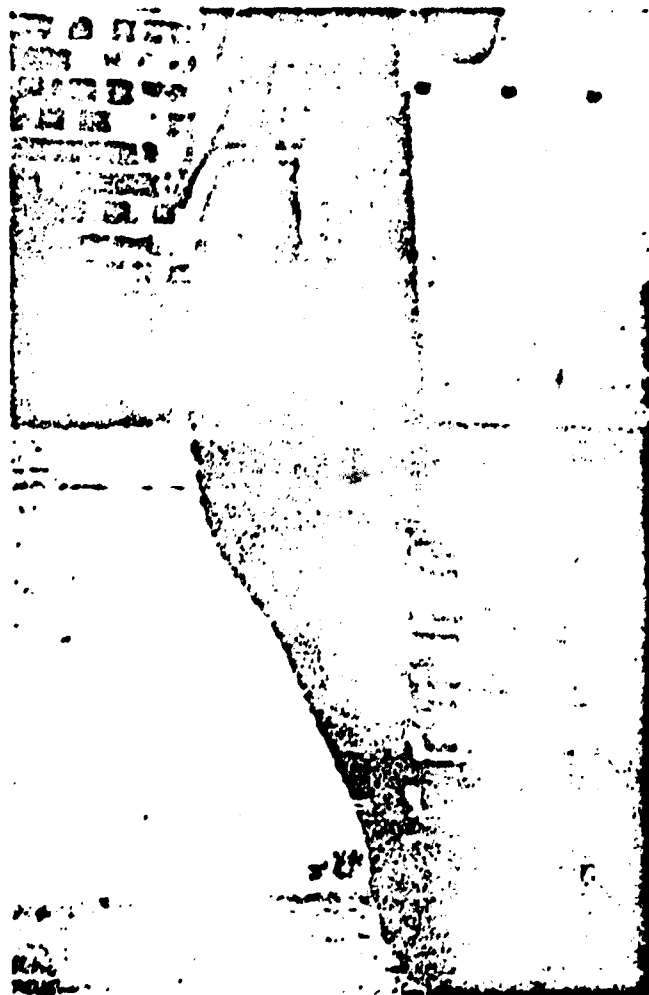
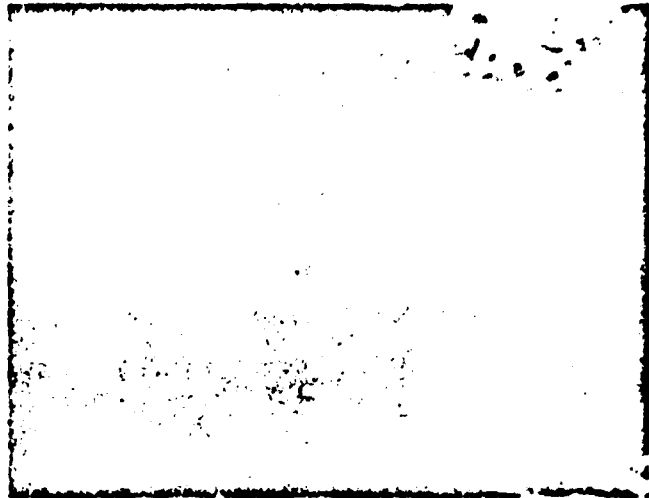
ral British T.V. 1000 6x6 Rhino [Ogorkiewicz, 1962], the recently proposed small 8x8 TILCAR [Armor, Sep-Oct 1966], and some short-coupled, rubber-tired construction tractors. For successful operation, however, L/T limits are even lower than on tracked vehicles, 1.25 being a practical upper limit [Adams, 1958]. The problems with proportions, maximum utilization of the platform for ground contact, and ride which have been discussed in relation to skid-steered tracked vehicles are accordingly compounded in skid-steered wheeled machines.

The advantages of vehicle articulation as an alternate means of steering, on both tracked and wheeled vehicles, were treated earlier. There is a third alternative on tracked vehicles, akin to the normal geometric steering of wheeled vehicles. Steering (down to a radius of approximately two vehicle lengths) by track warping or "track snaking" has been successfully applied to several small, light, narrow-tracked vehicles [of. Little, 1964]. Adoption of this mode of steering does not free the design from basic L/T limitations, however, and does not appear applicable to larger, heavier vehicles. Its main advantage is that it provides smoother, more stable, high-speed on-road control.

From the viewpoint of first cost, tracked vehicles are essentially competitive with off-road machines on tires, especially when either is compared to helicopters at \$50 per pound, or fixed wing aircraft at \$20 per pound [Reiger and Rubin, 1963]. Costs range from approximately 85¢ per pound for the large commercial production construction tractors, and approximately \$1 per

STEERING BY TRACK WARPING

ALECTO, 1941



pound for the high production M113 (Gorkiewicz, 1964), to approximately \$2.20 per pound for tanks and low production, special purpose commercial machines (Gorkiewicz, 1963, 1965). In comparison high performance, off-road military trucks run \$1-\$1.25 per pound in production (Jones and Lett, 1963), and may range to over \$2 per pound for highly sophisticated, low production machines such as the amphibious Alvis Stalwart 5-ton 6x6. Production costs for COER vehicles were estimated in 1963 (Reiger and Rubin) to be in the order of \$2 per pound. These overall "per pound" figures are directly comparable in light of the fact, already discussed, that the weight of each type of vehicle is essentially the same when the off-road performance is approximately the same (see, for example, WMEA, 1965).

Such composite cost figures, of course, mask many detailed differences. Important differences may be found, for example, in the weight, complexity, and hence cost, of the drive train. Needless to say, any off-road vehicles on wheels must have all-wheel drive. Thus there is considerable drive line complexity involved in such multiwheel configurations as the currently fashionable 8x8. In a conventional tracked vehicle, all wheels are driven (through the medium of the track) but the power is supplied only to one sprocket on each side. This makes for a basically simple power train layout. Moreover, the driven "wheel" (the sprocket) is unsprung, which simplifies matters

even further. While articulated tracked vehicles (which must have all-track drive) involve driving four sprockets, the basic complexity is still only that of the drive of a good 4x4 vehicle. As against this, in a conventional tracked vehicle, special transmission arrangements must be made to provide for effective and efficient steering [cf. Christensen, 1953], and in both conventional and articulated vehicles, a transmission which can be shifted without loss of headway is highly desirable, if not essential [Liston and Kanamoto, 1966], because of the intrinsically high rolling resistance of tracked vehicles even on hard ground.

The higher hard surface rolling resistance of tracked vehicles also means that, for the same speed as a comparable wheeled machine, more power is required. Speeds off-road, however, are generally traction or ride limited in both types, and the installed power per ton of gross weight turns out to be about the same (15-25 HP/T) for off-road trucks and for tracked vehicles. The penalty accepted is that the tracked vehicle will have a lower top highway speed.

Maximum on-road speeds of tracked vehicles are limited by practical considerations of wear, controllability, and road damage to approximately 30-40 mph. The land speed record for tracked vehicles may be held by C. W. Wilson, who in 1944 tested the T70 76mm gun motor carriage (which, detuned, later became the M113) at 70 mph.* He reports it was a hairy experience. Needless to

*Christie experimental tanks are reported to have run at higher speeds [Carlisle, 1964], but it seems probable that such runs were made with the tracks removed.

say, from the viewpoint of on-road speed, economy, and wear and tear on the vehicle (and on the road), the tracked vehicle is in no way competitive with a good vehicle on tires.

Converting installed gross horsepower and maximum speed to an equivalent thrust for a large number of vehicles of various kinds gives an overall effective drag ratio (R_d/W) of 0.07-0.8 for standard tracked vehicles as against 0.03-0.4 for all-wheel-drive trucks, and 0.05-0.10 for armored cars [TM 9-2800, 1943, 1947, 1953; Noville, 1956; Ordnance School, 1958; TM 9-500, 1962; Cleare, 1963; Cgorkiewicz, 1945]. The same figure (R_d/W) for current low ground pressure articulated vehicles appears to be about 0.11. It is not known at this moment whether the increment is an intrinsic cost of articulation, and/or of exceedingly low ground pressures, or merely represents lack of sophistication in detail design. For comparison, R_d/W for current skirted GEM's ranges from 0.40 for small machines to about 0.18 for those grossing 150 tons or more [Hovering Craft & Hydrofoil, Jun-Jul 1966].

The effective drag ratio (R_d/W) converts all losses between the advertised horsepower of the engine and the ultimate top speed of the vehicle on a level pavement to a single index. Actually, accessory loads on the engine (cooling fans, generators, pumps, etc.) absorb about 15-20 percent of gross horsepower of conventional engines, and transmission and drive line inefficiencies reduce power available at the wheels or sprockets by another 20-30 percent [Cleare, 1963].

Power at the sprockets or wheels must overcome the motion resistances of the vehicle beyond this point. These include further mechanical losses within the track system or tire, and external motion resistances. On a hard surface these arise largely from scrubbing losses in the contact area, grades, towed loads, and, at speeds above 30-40 mph, air resistance. Off-road, the internal motion resistance of tracked vehicles is increased by the ingestion of soils, snow, mud, vegetation, what have you, into the exposed working parts of the track system; and both wheeled and tracked vehicles encounter resistance from the flow and nonelastic yielding of the supporting surfaces, and from grades and smaller obstacles which must be surmounted or overridden.

Tests have shown that the towing resistance of trucks on a hard level pavement is of the order of 0.01-0.015,* while that of tanks is 0.04-0.05 [APC, 1945], of which 60-70 percent is mechanical losses within the track, sprocket, and guiding system [Cleare, 1963]. Little quotes track losses at road loads on a level pavement as being approximately twice those of wheel drive losses at 20 mph, three times at 30 mph [1964], and as tripling under maximum tractive loads [1961]. Road load losses in a tracked vehicle are reduced by the adoption of rear sprocket drive, large road wheels, and a design allowing the use of a relatively slack track [Cleare, 1963; Little, 1964].

*Fitting cross-country tires in place of highway tires is reported to increase the on-road rolling resistance of a truck by 5-15 percent [Krestovnikov, 1958].

The off-road speeds of current vehicles are generally ride^a or traction limited, rarely power limited. Also, in weak soils, the increment in motion resistance is large in relation to road load resistances (large grades are more often encountered, etc.), so that the percentally large advantages of wheeled vehicles over tracked vehicles on hard level roads are not reflected in significant off-road speed differences between comparable tracked and wheeled vehicles. Cleare has estimated that general cross-country operation of a tank involves the same average power expenditure as continuously climbing a 10-percent grade, which is the same as saying that the average increment of R_e/W is about 0.10. He also quotes field test results on tanks indicating that the increment for a tracked vehicle operating in level sand is of the order of 0.10; in mud, 0.17; and, at the point of bellying-out in weak soil, 0.65 [1963].

It is in the area of operating costs and operating problems that the tracked vehicle is most at a disadvantage, especially when it is used largely in relatively favorable conditions. The Hydro Electric Power Commission of Ontario found

^aLahr, in 1944, enunciated as an objective of tank suspension design to allow a tank to negotiate 12-inch sinusoidal roughness at 30 mph, and a single 16-inch high obstacle at 35 mph. These objectives have yet to be achieved. Considerable attention being devoted to off-road vehicle ride in rough terrain has the general goal of increasing average maximum practical speeds from the order of 5-10 mph, or in extreme cases as little as 1 mph, to such speeds. It is interesting to note that the "cross-country" racing speed of horses and riders in the Grand National Steeplechase is approximately 24 mph. (Flat course horse racing speeds are of the order of 38 mph.)

that by switching from low production, commercial, low ground pressure tracked vehicles to an adaptation of the Canadian 4x4 mulwood machines for right-of-way maintenance, overall costs were reduced by 20 percent [Campbell, 1965]. Certainly fuel consumption is somewhat higher by virtue of the generally greater motion resistance. Cleare [1963] quotes on-road fuel consumption for gasoline powered, tracked vehicles as 18 ton/mile per gallon as contrasted to 60 ton/mile per gallon for wheeled vehicles. In average off-road conditions, the comparison would be more of the order of 10 ton/mile per gallon for tracked vehicles and perhaps 20 ton/mile per gallon for wheeled vehicles. Presumably this general order of relationship would hold for completely comparable tracked and wheeled vehicles.

When tested against a difficult off-road terrain, the situation is a little different. In a study of ground effect machines for possible Army use, Booz-Allen [1963] calculated the following overall operating costs per one-way ton-mile in an assumed traverse of a mixture of difficult but not extreme terrain conditions:

Tracked RN-110	61¢ per ton-mile
5-ton standard 6x6	95¢ per ton-mile
5-ton GCER 4x4	58¢ per ton-mile

Abele [1965] quotes Greenland tractor train operation as \$1.50 per ton-mile. All of these compare favorably with various air-assisted or airborne craft for cross-country work as follows [Booz-Allen, 1963]:

Pure ground effect machines	\$8.86 per ton-mile
Chinook helicopter	\$3.61 per ton-mile
A. V. Poe Gemini (4x4 with optional air support)	\$2.69 per ton-mile
Optimum wheeled vehicle with air cushion assist	\$1.82 per ton-mile

For some perspective only, long-haul jet freight costs in 1963 were only \$0.05 direct cost per available ton-mile (two-way) [FAA, 1964].

The largest area of deficit for tracked vehicles is in durability and maintenance. The life of a well-designed military track is currently of the order of 3,000 to 5,000 miles, and if used on the highways with road pads, the latter must be replaced at 1,000- to 2,000-mile intervals. Track replacement costs alone on the M60 run to \$2 per mile; on the M113, \$64 per mile. Ontario-Hydro experience with small and medium commercial, low ground pressure tracklayers in right-of-way service was that their maintenance costs were \$5-\$7 per hour of operation and totaled one-third of vehicle cost per year. Overall vehicle maintenance costs were reduced 75 percent by the change to articulated 4x4 machines for the same duty [Campbell, 1965].

The maintenance disadvantage of tracked vehicles is fundamental. The track is a highly stressed chain operating exposed in a hostile environment. Most of the excess of power expended in a tracked vehicle as compared to a wheeled vehicle goes to grinding away this chain and its support system. Only partly mitigating this are the facts that tracked vehicles are generally expected to take rougher treatment than wheeled vehicles, and that they get it.

The question of wheels versus tracks is far from clear cut. If it were not, constant study of the question would of course be at an end.

Although comparisons of current tracked and wheeled vehicles confirm that in the limiting off-road conditions tracked vehicles perform better [Depkin,

1964], there is far more that can still be done with wheeled vehicles [cf. VMA, 1965]. The ultimate maximum of mobility in a given package will, however, be obtained from a tracked vehicle. Accordingly, it behooves us to study all possible mechanical means to improve the economy and reliability of track systems. Much may yet be possible, as Little has pointed out [1964].

In the final analysis there can be no general solution. The job requirements, the level of performance required, converted to proper testable specifications, will dictate the choice. No arbitrary weighting [cf. Lucas, 1961] can do so. The choice should be left to the vehicle engineers.

And it is questionable whether when, as now, we are fighting a left-handed war, we have the moral right to let cost enter materially into considerations of how to equip our combat troops. In an editorial of 26 June 1966, the *New York Times* seconded Congressional action which rejected cost/effectiveness as a consideration in traffic safety, where human lives are at stake. At our present juncture, with less than 0.2 percent of our population actively imperiled in a shooting war, the same ethic should prevail. Once actual dollar costs are removed from the wheeled-versus-tracked problem, it does in fact become resolved, for areas like Vietnam, in favor of tracked vehicles.

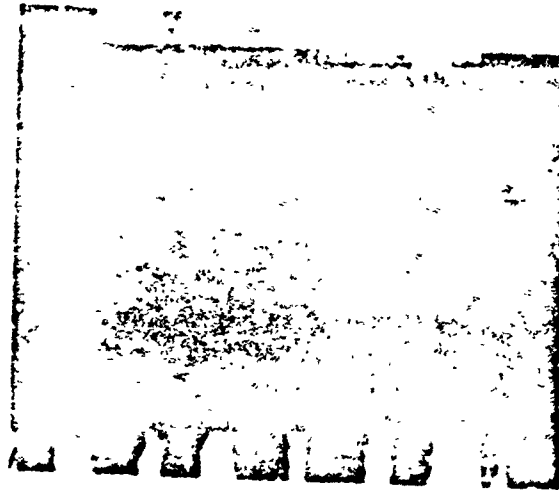
What Is a Tank?

Everyone knows what a tank is. A tank is a tank killer [DeMont, 1965], a tank is a weapon [Scherrer, 1964], a weapon system [Shiovitz, 1966], not a vehicle. Today's main battle tank is a collection of more than 100,000 parts [Snider, 1964], costing nearly one-quarter million dollars [Ogorkiewicz, 1965], capable of accurately discharging approximately one-two tons of projectiles upon line-of-sight targets up to a mile and a half away, within a period of about eight minutes. It is an important item of export trade for the United Kingdom [Ogorkiewicz, 1962, 1963], France [Ogorkiewicz, 1966], and the United States [Besson, 1965; Shiovitz, 1966]. The effective design of a tank is a major exercise in systems analysis and engineering.

The first tanks to see battle were the British Mark I's, on the Western Front at Sommes in 1916. One-half hour before dawn on 15 September, 49 of the unfledged and ungainly beasts began lumbering into position to support an otherwise ordinary infantry attack preceded by the usual rolling barrage. Thirty-two reached their assigned positions as dawn broke and the attack began. Of these, 18 actively took part in the battle and passed the trench lines to first success, 9 broke down, and 5 ditched [Williams-Ellis and Williams-Ellis, 1913]. These primitive machines lacked both reliability and, in many situations and respects, mobility. These two problems still dog modern tanks.

In the creation of the Mark I, the designers were for the first time, and perhaps for the last time as well, given clear, quantitative, functional specifications, and a bare minimum of constraints.

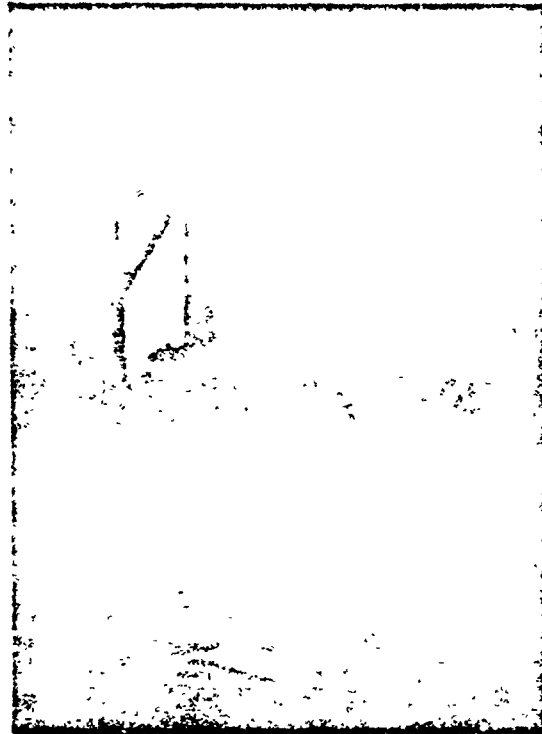
ANTITANK WEAPONS



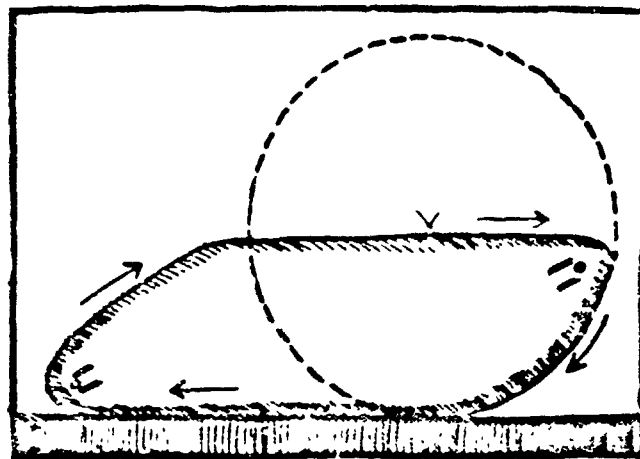
The machine was intended to provide mobile fire-power and armor protection against the machine guns which, behind barbed wire and trenches, had produced the gory stalemate on the Western Front. The mobility required was determined by a study of the job to be done. As a result of the study it was specified that the machine be able to climb a 4-foot-6-inch parapet and to cross a 5-foot (shortly raised to 10-foot) trench. The first response to these requirements were concepts on large wheels -- up to 60 feet in diameter. Although the ridiculousness of such wheels on the battlefield was soon apparent, the final machine on tracks consciously preserved the wheel form [Stern, 1919; Williams-Ellis and Williams-Ellis, 1919].

As noted in the introduction, tank design had by 1929 become far more frustrating, in large part because the job to be done by a tank could by then no longer be clearly specified [OCM Item 7814, 1929]. In the 37 years since, tanks have been designed in accordance with a wide variety of mission and operational concepts, with large differences in armament, mobility and level of armor protection (cf. Carver, 1966). Today there are fewer classes of tanks and there is less difference between the capabilities of the tanks of each country [Lynde, 1959], as is perhaps to be expected, since all designers have faced the same general problems [Icks, 1961] and solved them within essentially the same technological constraints. However, the question of the optimum design priorities or balance between conflicting desires for firepower, mobility, and protection, with reliability always given a high priority, remains.

MOTHER AND THE WHEEL



Stem, 1919



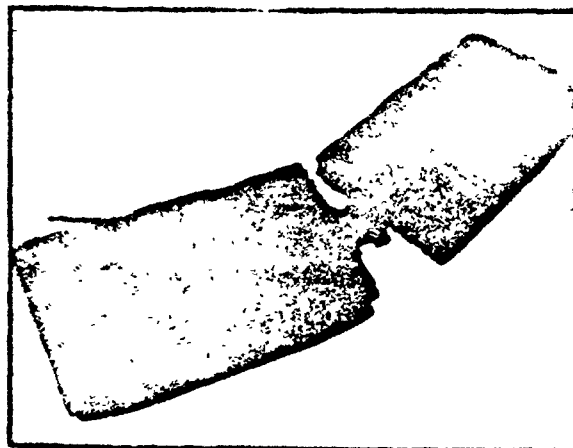
Ellis, Ellis, 1919

The job of a present day tank is variously described. The consensus appears to be that its role is to provide a mobile source of direct fire support for use against battlefield targets within visual range. The most formidable such target is another tank. Hence tank-versus-tank action, today at ranges up to more than 2000 yards, becomes a major design consideration [Ogorkiewicz, 1963, 1964, 1965; DeMont, 1965]. An Army Materiel Command spokesman has been quoted to the effect that in the design of the new main battle tank for the 1970's (MBT-70) now under joint U. S. and West German development [Lesson, 1965; Vance, 1965], the object was to obtain "the most tank that will defeat known enemy tanks on the future battlefield, at the least cost" [Watson, 1966]. Up to the near present, tank-versus-tank combat appears to have favored fitting the conventional, high pressure tube gun (105mm or 120mm on current main battle tanks), which can be rapidly laid on targets of opportunity and can dispatch 8-18 rounds per minute (depending on caliber and loading scheme) with deadly accuracy and high penetrating power [Parker, 1965; von Usler-Gleichen, 1965] even against double skin designs which may frustrate lower speed missiles which depend upon a shaped charge for penetration [Moore, 1966].

There is no unanimity as to the work of a tank, however. Another viewpoint proposes that its role should be entirely offensive, to destroy enemy infantry, supply lines, and weapons by firepower and shock effect [Scherrer, 1964]. While conceding that a tank is the best antitank weapon, it is argued that such use is defensive, and hence is a secondary role, and that the design

of the tank should therefore not be compromised by tank-versus-tank considerations. The design should rather stress speed, mobility, agility, and range. By implication, this viewpoint turns the job of defeating enemy tanks over to "tank destroyers," which are generally mobile and tactically agile, heavily armed, lightly armored, and without turrets. Although both the U. S. and the German armies had great success with tank destroyers in WWII [Cole, 1965; Louis, 1965; von Usler-Gleichen, 1965], the United States abandoned the tank destroyer concept in 1946 [Louis, 1965]. At present the thinking of the west German army [von Usler-Gleichen, 1965] and perhaps of the French army as well [Ebert, 1964] appears to favor development of modern ground-crawling tank destroyers; while in this country, and perhaps in Great Britain, attention may be turning to missile-armed helicopters for such a role [Holladay, 1965; *The Engineer*, 25 Jun 1965].

While thus far generally classed as a tank, because it appears intended to face it out with other tanks rather than to hit and run, the low, turretless Swedish "S" tank [Ogorkiewicz, 1964, 1965; Barclay, 1965; Skolman, 1966; Icks, 1966] has many of the characteristics of a tank destroyer, and may perhaps better be classed as a hybrid. Although this may only be an exercise in semantics, it illustrates that the lines of division between tanks, tank destroyers, and gun carriages are indistinct, and will become still more blurred if, in the future, further sacrifices in armor are used to improve mobility rather than fire-power.



Forsyth prizewinner, 1963



Swedish "S" tank, 1964

In any tank design, the weight and space requirements for firepower, mobility, and armor protection are obviously in conflict with each other, and with cost, overall dimensional limits, and reliability as well. As an illustration of one facet of the problem, Table VII presents the allocation of weights to various functions for three U. S. tanks of the recent past.

The various primary elements of a tank design, its gross weight, its gun, its level of armor protection, its NUGP and speed, and its dimensional envelope, are so closely interlocked in the conventional form of tank that immediately one or another is fixed, those remaining begin to be seriously constrained. Butterfield has put it that after an early point the tank "designs itself," particularly as regards to its off-road mobility potential [1966]. Accordingly, radically new levels of performance can only be achieved by radical changes in design balance and/or in form and concept [DeMont, 1965].

Firepower is reflected by the size of gun mounted, its accuracy, its rate of fire, and the quantity of ammunition carried. The 120mm gun used on the 58-ton British Chieftain weighs over 6000 pounds. Its two-part ammunition, of which it probably carries about 60 rounds, weighs 100 pounds per load and can be fired at the rate of 8 rounds per minute [Ogorkiewicz, 1962, 1963, 1964]. Thus, for this tank, the gun and ammunition alone and unarmored, unmounted, weigh 5 tons. Firing a high pressure tube gun of this size develops trunnion reaction forces of the order of 75 tons [Ogorkiewicz, 1962; DeMont, 1965], which cannot reasonably be managed by a lightweight

TABLE VII
SAMPLE WEIGHT BREAKDOWNS FOR TANKS
 (APG, 1945; Noville, 1956)

	<u>M4A1</u> <u>1945</u>	<u>M24</u> <u>1946</u>	<u>M49A1</u> <u>1955</u>	
GVW (T)	33.5	20.3	52.9	
HP/T	10.5	10.8	15.6	
NUGP (psi)	13.5	10.5	11.8	
Gun (mm)	75	75	90	
Hull	28.9	15.6	29.4	Armor = 40% (and structure)
Turret	12.4	10.9	13.9	
Power Plant & Power Train	14.7	14.7	12.2	Mobility = 40%
Suspension	12.2	16.9	14.3	
Tracks	8.9	9.5	9.0	
Fuel & Tanks	2.4	2.8	2.4	
Guns, comp.	5.8	5.1	5.2	Firepower = 13%
Ammo & Racks	5.0	5.2	5.0	
Electrical	2.2	1.5	2.0	
Personnel, Stowage, etc	7.5	7.8	6.0	Misc. = 7%
	<u>100.0</u>	<u>100.0</u>	<u>100.0</u>	

vehicle in any event. All of which simply illustrates that modern tank firepower is costly in terms of weight (as well as dollars).

That armor *per se* also costs weight (and space) needs still less demonstration. The weight of armor is a direct function of the volume of the tank's armored spaces, and, with armor distributed in about the normal fashion, is approximately $45/t$ pounds per cubic foot, where t = the basic maximum steel armor thickness, in inches, of the tank as a whole [Noville, 1956]. The use of aluminum armor, as on the M113 and the hull of the new XM551 Sheridan air-transportable reconnaissance tank [Simpson, 1965], saves only about 6 percent in weight, for the same level of protection against direct fire [Ogorkiewicz, 1962]. The volume armored in a given tank is the sum of volumes required to enclose its main and any auxiliary weapon systems -- aiming and control mechanisms, loading arrangements, ammunition, and the crew to operate it all -- and its mobility system -- power plant, power train, fuel, and driver(s). This is one important reason that current tank engine developments stress high output per unit of installed volume and low fuel consumption even more than high output per unit of installed weight [Lux, 1964; Butterfield, 1966; Williams, 1966]. Trade-offs are possible at this level also, between space and fuel consumption, as on the Swedish "S" tank. This machine has a dual power plant consisting of an efficient 240-HP diesel for general use and a compact but relatively high consumption 300-HP simple gas turbine to supply peak powers [Ogorkiewicz, 1966; Kronogard, 1966], which in the presumed "battlefield day" may only

be required about one-quarter of the time [Hayter and Gilvydas, 1964]. Similar considerations dictate that the crew be kept to a minimum, because each man requires 55-75 cubic feet of living space, depending on his function [Noville, 1956].

The value of armor protection is generally conceded to be small against well directed 105mm and 120mm guns as now carried on main battle tanks, which can penetrate 15 inches of steel armor at 500 yards if a hit strikes it squarely [Icks, 1964], and against well placed hits by modern missiles [Holladay, 1965]. Well and properly shaped armored hulls and turrets, which greatly reduce the probability of a 90-degree hit, mitigate this significantly. The Russians appear to do a particularly effective job in this regard [Miller, 1965], at the expense, in their turrets, of limiting possible gun elevation and depression to values not considered acceptable by western designers [Gorkiewicz, 1962]. The current general trend in armoring appears to be to determine "how little" is needed [Shiovitz, 1964] to deal with fire from specific types of weapons [Parker, 1965] likely to be encountered in large numbers, rather than to attempt complete protection against either tank guns or antitank missiles in the field, or to accept an arbitrary weight limit.

Since Hiroshima, armor has also been considered for protection from radiation, heat, and blast in an atomic battlefield [Howze, 1961; Vance, 1965]. However, protection from gamma radiation from a 20 kiloton blast at 125 yards requires 18 inches of steel armor (weighing 600 pounds per square foot of hull surface);

neutron protection from the same blast, 33 inches (1000 lb/sq ft) [Gray, 1964]. Armor on the M60A1 reduces outside radiation levels by 75 percent [Parker, 1965] which, while not adequate protection from a close blast, is apparently considered potentially useful.

Where does all this leave mobility? Some published comments on design priorities over the years and from country to country are briefly summarized in Table VIII. According to this qualitative and somewhat superficial summary, mobility has generally rated second priority, most usually second to armor protection prior to WWII, and to firepower in more recent years. In a previous section, Table IV illustrated that the soft-ground-crossing mobility of medium or main battle tanks has remained of the same order since 1916; and Table V, that it also appears to be of the same order among all of today's competitive machines. Some additional indices of performance potential are listed in Table VIII, along with main gun bore (as a measure of firepower), and gross weight and vehicle height* (as crude measures of armor protection). Insofar as the tabulated figures refer to mobility, they illustrate once more that it has increased only marginally since WWII. Gun sizes have clearly grown, while gross weights have stayed reasonably stable, indicating that firepower has indeed taken precedence over armor protection in recent years.

*Low height offers more protection from a hit by another tank than does reduced length or width because vertical ranging errors are relatively larger than horizontal laying errors [Ogorkiewicz, 1965].

TABLE VIII

MICHIGAN BALANCE

MAIN DATA 1941-1943, 1945-1946

From published data and discussions.
(See Table IV for references to test data)

	on Main Data	QTY	Po. Weight	pod MUP Elev.	Co. Elev.	Po. Vert. Step-41.	Po. Trench Meter	W/T Load 194.	W/T Load 194.	PROTECTION	DISCUSSION REFERENCE
WTI	U.S.	31	0.2	12.0	16	4.5	10.0	0.1	1.7	M 0 F	Starn, 1919; Carver, 1966
1930's	Various									M 0 F	Carver, 1966
1930's	Various									M 0 F	Opertown, 1963; Carver, 1966
WTI	U.S.	26	0.7	13.2	17	2.0	0.5	13.0	25	M 0 F	Opertown, 1963
U.S.	Centurion II	77	0.6	13.5	20	2.0	0.5	11.1	22	M 0 F	Opertown, 1963
Germany	Panther	80	0.6	12.5	21	2.0	0.5	13.9	20	F M 0	
Russia	T34-86	85	0.6	10.0	15	2.5	0.2	10.3	23	M 0 F	
1940's	U.S.	125	0.6	11.1	18	3.0	0.5	14.0	30	F M 0	Parber, 1963
U.S.	Chieftain	120	0.6	10.5	20			14.2	25	F 0 M	Opertown, 1963; Carver, 1966
Germany	Leopard	185	7.0	11.5	18			10.0	41	M 0 F	Green, 1964; Meyer, 1966
Russia	T34/86	140	7.0	10.5	17	3.0	0.5	14.2	31	F M 0	Miller, 1963, 1946
	T10	122	0.6	9.0	18			13.0	21	F M 0	
France	AMC30	105	7.5	10.0	18			19.1	40	F M 0	Beament, 1963; Opertown, 1966
Sweden	0	90	7.0	11.0	16			14.2	31	M 0 F	

Inations studied, however.

M = Mobility
F = Flammable
0 = Armor protection

Accordingly, what has in fact been meant by holding mobility in second priority over the years is that the basic level of mobility of tanks at the close of WWII has been generally accepted as a practical minimum, with the result that design readjustments to increase firepower have been made at the expense of armor protection rather than mobility.

Of course, firepower, mobility, and armor are not truly separable. Firepower and armor require mobility for their exploitation [Lynde, 1959]. In recent articles on the use of armor in Vietnam and on the upcoming XM551 Sheridan, the priorities have been listed as mobility, fire power, and *shock effect** [Battreall, 1966; DeMont, 1965]. The ability to employ the firepower of a vehicle-mounted weapons system in time and space, "to concentrate, to envelop, to deny . . . which constitutes mobility" is as important as the weight of fire delivered, even though not as readily quantified [Rice and Hatch, 1966].

Despite grim reports of regular vehicle immobilizations in Vietnam, properly designed armored vehicles could play a leading role there [Moore, 1966]. Much of the highlands is good tank country during the dry parts of the year when our present tanks can operate without bogging [Raymond, 1965]. At present, however, the M113 is the backbone of armored vehicle operations, performing the

*The term "shock effect" appears to be the product of firepower and mobility as suggested by Montgomery, who has written: "The power of an army is its weapon power multiplied by its mobility" [1965].

job of providing mobile firepower which is a tank's, simply because "it can move," and because in spite of its problems in getting out of rivers and canals, it can, after a fashion, negotiate these everpresent water obstacles [Battreall, 1966; Moore, 1966]. Vehicle-mounted bridging systems designed to give tanks mobility in these situations [Ivey, 1965] have thus far proven more a problem than a solution [Battreall, 1966].

The XM551 Sheridan, now going into production [Defense Industry Bulletin, March 1966], may prove to be the main battle tank for Vietnam. Details on this vehicle have not yet been released, but it is reported to have ground mobility far superior to that of current tanks [Simpson, 1965], to swim, to weigh about 16 tons, to be diesel powered, with an aluminum armor hull, and to be armed with the turret-mounted Shilleghli weapons system [DeMont, 1965] which is considered potent enough to replace the 105mm gun on new M50A1 chassis and to be considered for the main armament of the MBT70 [Watson, 1966]. Its basic soft-ground mobility parameters may be estimated from the little published data. They appear to compare favorably with those of the successful M113A1, as shown in Table IX.

TABLE IX
SOFT-GROUND MOBILITY FEATURES OF THE SHERIDAN

	<u>Sheridan</u>	<u>M113A1</u>	<u>M77</u>
GW, T.	16.5	12.0	16.5
NUGP, psi	6.9	7.6	6.9
HP/T	18.1	17.9	18.1
VCI	45	50	31
VCI ₁	27	29	15

The table also shows the results of a brief study of the possibilities for a similarly armed and armored, soft-ground, low ground pressure, articulated vehicle (the M77), which indicate that considerably more soft-ground mobility is still available if needed. It has also been suggested recently that hovercraft might be useful as tanks, in Vietnam and elsewhere, although the scope of problems which would require solution is substantial [Beaumont, 1966].

It is evident that the proper balance between firepower, mobility, armor protection, and form in a tank is a matter for careful systems analysis. It is also evident, both from common sense and from the published colloquy, that the mission, and particularly the geographical area in which the mission is to be accomplished, must be specified. A systems analysis deals with the fundamentally impossible task of striking a balance between factors which are totally unlike. This can only be done upon a limited, specified basis [Rice and Hatch, 1966], and even then only approximately. The result of any such analysis, when basic

terrain and operating conditions are as different as those of Europe and of Southeast Asia, must either be two distinctly different machines or a single machine so badly compromised as to be nearly useless in both environments.

Stephens, in recounting WWII problems in injecting the successful DUKW 2-1/2-ton 6x6 amphibian into the military system, commented: "Too frequently, development of new equipment is hampered by erroneously considering that it competes against some other very different type of equipment" [1944]. The Sheridan, or an armored hovercraft, or any other mobile firepower platform suitable for use in Southeast Asia will not necessarily be a tank in usual European battlefield sense, and will not be competitive with our current European style tanks, either in Europe or in Asia. Nor must it pass muster as universally useful [Vance, 1965]. After all, no one can any longer claim that our current tanks are.

One computerized systems analysis has already been applied to the tank problem, with what success remains to be seen. In August 1963, agreement was reached between the Federal Republic of Germany and the United States to jointly design a single main battle tank for use in the 1970's, the MBT70 [Besson, 1965]. The project began with a "rubber tank" or parametric computer study by Lockheed to determine functional requirements for a tank to be used in Europe [Orkance, May-June 1965; Chiovitz, 1966; Watson, 1966]. Design priorities are reported to have been fire power, mobility, and survivability, in that order [Army, May 1965]. By the summer of 1965, the conceptual approach and technical characteristics had been agreed upon, major components had been

agreed upon [Desson, 1965; Vance, 1965], and prime contractors selected.

While it is known that the mission for which the optimum MBT was to be defined by the study was tank-versus-tank combat in the European theatre, the value system used has not been disclosed. Presumably it was some sort of probability of success, such as Gorkiewicz has recently outlined [1965]. Probability of success (P_s) is the joint probability of availability, the chance that the tank will be where and when it is needed (P_a), the probability that it will survive (P_e), and the probability that it will be able to kill the opposing tank (P_k); i.e.,

$$P_s = P_a \times P_e \times P_k$$

In this formulation, mobility is included with agility, reliability, and transportability in the availability term.

According to published reports, the MBT70 growing from the studies, in addition to mounting the Shilleghli weapons system in a turret [Watson, 1966], will be suitable for the nuclear battlefield and will be a floater, powered by a variable compression ratio multifuel engine giving twice the horsepower per ton of present tanks [Automotive Industries, 1 Dec 1965; Quinn, 1966]. Its soft-soil mobility features have not been mentioned, but it seems probable that they will differ but little from current tanks. Its rough terrain performance, however, should be at least as good as the current German Leopard, which is reported to be "remarkable" [Meyer, 1966].

But all was not be roses. The Federal Republic of Germany and the United States will each build their own pilots, ostensibly to demonstrate interoperability [Watson, 1966]. However, there is already speculation that these will instead be two different machines, representing two different, competitive interpretations of the study results, with the German machine perhaps stressing mobility more than the U. S. [Shiovitz, 1966].⁹ Which illustrates that even careful systems analyses do not, in such a complex problem, produce unequivocal results.

⁹In the late 1950's, Germany, France, and Italy developed tripartite tank specifications in a similar effort at standardisation. The result was the German Leopard and the French AMX30, while Italy decided to buy M60's [Icks, 1964; Ogorkiewicz, 1966; Shiovitz, 1966].

Amphibian Blues

The design of a good boat for a given service is complex but manageable. Design of a successful off-road vehicle is still more complex, and less manageable. When the two design areas are compounded in the creation of a swimming vehicle, which must cope with the problems both of boats and of off-road vehicles, plus some new ones at the land-water interface, the situation becomes frustrating at best. As much as with a conventional tank, the swimming vehicle, confined within a dual set of physical constraints, almost designs itself.

Amphibious vehicles go back to the "Amphibolos Orkuter," built in Philadelphia by Oliver Evans in 1804 [Manley, 1954; IKD, 1955]. The first serious military interest in amphibians, however, was evoked by several prototype tracked, screw-propelled, amphibious "tanks" built by Christie during the early 1920's, but these were found wanting at the time [IKD, 1955]. U. S. Navy and Marine interest was revived in 1935 by Donald Roebling's tracked, track-propelled "Alligators," conceived for rescue work in the Florida Everglades. This time the spark did not die. In the few years following, the successful LVT vehicles of WWII were developed [IKD, 1955], and with them the amphibious assault doctrine which retook the Pacific in 1943-45. Navy and Marine Corps landing vehicle development has continued, resulting in a series of increasingly large, 5-7 knot, tracked track-propelled vehicles suitable for beach assaults [Alexander, 1957; USMC, 1964; Buships, 1964]. The latest in this direct line of descent is the experimental tracked LVT(X)12 25-man carrier, with twin water jet

propulsion, diesel engine, and a bulbous bow [Armor, May-June 1966].

A second line of amphibian development was initiated by the National Defense Research Committee of OSRD in 1941, with the conversion of the standard 1/4-ton 4x4 jeep to a screw-propelled amphibian [OSRD, 1946]. This approach quickly came to fruition in the conversion of the WWII 2-1/2-ton 6x6 to the spectacularly successful DUKW, which first saw action in the landings in Sicily in July 1943 [Stephens, 1944; OSRD, 1946]. The DUKW was conceived essentially for unloading ships in a continuous flow from shipside, across sand beaches, to inland dumps with no delays and pile-ups at the water's edge. Implicit in this concept was the ability to land through high surf. In this regard in particular, the DUKW exceeded all expectations, setting a standard which is hard to beat today. However, at the war's end, the consensus was that the DUKW still left much to be desired. It was too slow in the water, inadequately mobile off-road in mud and other weak soil conditions excepting sand, carried too small a payload for efficient ship unloading, and was itself troublesome to load and unload [Stephens, 1944; OSRD, 1946; Manley, 1954]. In the ten years following WWII the Army attempted to correct these deficiencies in a series of wheeled amphibians patterned essentially after the DUKW -- the Superduck 4-ton 6x6, the plastic-hulled Gull 5-ton

6x6, the Drake 10-ton 8x8 [Joy, 1956; Roach, 1960; Grigore, 1965]. While these machines did carry larger payloads at modestly higher water speeds, their mobility was not improved, as shown in Table X, which summarizes the mobility indices (developed in Appendix III), payload capacities, and water speeds for a number of wheeled amphibians and floaters.

A different direction, based upon the use of simpler 4x4 unsprung ground running gear, and hence implicitly placing greater emphasis on water capabilities, was begun in 1952 with the construction of the mammoth 60-ton payload BARC [USMC, 1964]. This has been since followed by similarly conceived, smaller, aluminum-hulled 4x4 machines, the 5-ton payload LARC 5 and the 15-ton LARC 15, which are now in service [Roach, 1960; USMC, 1964]. The LARC's have modestly improved water speeds and, between them, appreciably increased payloads over the DUKW levels. Loading and unloading are also speeded through adoption of an open-sided cargo deck which may be loaded and unloaded by means of forklifts working from the sides. However, as indicated in Table X, except in their sand performance, their calculated soft-soil mobility is either worse (LARC 15) or only marginally improved (LARC 5) over that of the DUKW.

To explore the cost/effectiveness of a truly significant gain in water speeds, the Navy has followed up studies initiated by the Army [Kamm and Finelli, 1957] and constructed two types of aluminum-hulled, gas-turbine powered, 5-ton payload amphibians, one designed for planing (LVN's), the other for high-speed operation on hydrofoils (LVH's) [Buships, 1964; *Hovering Craft and Hydrofoil*, Nov 1964, Feb 1965]. Both types are 4x4's with retractable wheels; neither offers any evident gain in soft

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soil mobility over the DUKW (see Table X). Although complex and costly, the hydrofoil LHX2 appears quite efficient from the viewpoint of fuel consumption at speed in the water, producing 2.8 ton-miles of cargo movement per gallon of fuel, as compared to 2.2 ton-miles per gallon for the DUKW and 2.5 ton-miles per gallon for the LARC 5.

And finally, current doctrine, growing out of the 1960 MOVER study [1960], says that all tactical Army vehicles should be inherently capable of negotiating inland water obstacles. This has been interpreted to mean that they should float with little or no prior preparation (preferably upright) and be able controllably to swim at speeds of at least 2-3 mph. These qualities are being built into the current new generation of tactical trucks. To distinguish them from their speedier, more seaworthy, surfing cousins, just reviewed, they are termed "floaters" rather than amphibians. Their mobility characteristics and their marginal water performances are also briefed in Table X.

So why the blues? First, none of the vehicles -- amphibians or floaters -- synopsized in Table X has adequate mobility to get out of the water under its own steam once it is in, except over sand beaches or under especially favorable and unusual bank conditions. Moreover, our tracked amphibians and floaters are little (if any) better in this regard (cf. Moore, 1966). Second, the laws of hydrostatics and of hydrodynamics do not allow any cheap and easy ways to improve water performance, regardless of the continued optimism of specification and requirements writers. And finally, the dictates of design for good water performance are, at many points, after the general cussedness of

things, at loggerheads with those for good off-road performance, particularly at the land-water interface, where mobility problems are regularly exacerbated by weak, wet soils and/or extreme, though sometimes short, grades.

The elements of water performance are simple and cannot be overlooked. The vehicle floats, upright, or it does not. Water is a simple enough substance that a speed is a speed, with little ambiguity once draft, channel, and current effects are recognized. Controllability or lack of it is readily apparent. And even surf performance can be specified and checked. One result of all this is that the compromises which must inevitably be made between water performance and the unavoidably more nebulous quality, off-road performance must favor the former. And its corollary is that, more often than not, soft soil mobility of the amphibian is *less* than that of comparable land-bound trucks, despite the fact that it *must* be more if it is to be able freely to get to and from the water's edge. This problem can be made more tractable by formulating realistic specifications for water performance.

Any amphibian or swimmer, as a body which must float, must be designed in accordance with Archimedes' law, by which its gross weight and its minimum dimensions are related. More detailed considerations of the desired attitude in which the body should float further limit the arbitrary selection of dimensions, and tend to dictate form and weight distribution and hence overall layout. In the design of amphibians and floaters of reasonable size, the problem is complicated by the fact that feasible overall dimensions are

limited by land-going and/or transportability considerations. Thus, while the planform loading (W/A) of work boats in the range of 5-20 tons gross displacement varies approximately as $0.01 \sqrt[3]{GVW}$ [Muttall and Hecker, 1945], that for non-swimming off-road trucks in the same range varies approximately as $0.03 \sqrt[3]{GVW}$, and for tracked vehicles as $0.04 \sqrt[3]{GVW}$. In practice, wheeled amphibians have struck a compromise -- $W/A = 0.02 \sqrt[3]{GVW}$. Tracked amphibians, being less free to increase their length, have tended to retain more compact, land-going plan dimensions -- $W/A = 0.035 \sqrt[3]{GVW}$.

Planform dimensional limitations, and particularly width limitations, mean that the inherent roll stability of the buoyant form is limited, so that the vertical center of gravity of the loaded machine must be kept relatively low. The problem is often aggravated, especially on wheeled vehicles, by cut-outs in the hull at the sides for running gear, which, when they pierce the waterline, still further reduce inherent form stability.

The second result of the high loadings of swimming vehicles is that their underwater shape

As shown in an earlier section, the actual variation for non-swimming trucks and tracked vehicles is given more nearly by $W/A = K \sqrt[3]{GVW}$. The more approximate forms are used here to facilitate simple direct comparison within this limited weight range. The change in the form of the relationship between W/A and $\sqrt[3]{GVW}$ for amphibians from a square root to a cube root is simply a reflection of the immutable laws of hydrostatics. Increase in loading in the water as $\sqrt[3]{GVW}$ would mean that the draft of the machine increased more rapidly than its planform dimensions, resulting in a systematic change in proportions with size which does not in fact obtain.

must be basically poor in terms of drag, propulsion efficiency, and control. This situation is again compounded by the usual presence as a gainly appendages to the hull some or all of the land running gear. The fundamental hydrodynamic problems involved were outlined by Huttall and Hecker in 1945, and by McEwen in 1947.

Ordinary boats and swimmers which are sustained in the water primarily by buoyant or hydrostatic forces at all operating speeds are termed "displacement" craft. The resistance to forward motion of such vessels comes from surface wave-making, skin friction, and the drag of submerged appendages. In amphibians, at a speed such that at $V/\sqrt{L} = 1$,^{*} it is estimated that approximately 40 percent of the resistance comes from wave-making, 30 percent from friction, and 30 percent from appendages [Whitney, 1955]. The skin friction of a given hull increases approximately as $V^{1.825}$, and its appendage drag as V^2 . Wave-making resistance also increases about as V^2 up to a speed such that $V = 0.9 \sqrt{L}$. Above this critical speed, the wave-making component of resistance increases, with some anomalies, approximately as V^3 or even V^4 . In merchant ship work, speed-length ratios of 1.1 or 1.2 are considered the economical upper limit of speed [Russell and Chapman, 1939]. A 20-ton round-bottom pleasure boat has a resistance/weight ratio (R/W) of the order of 0.0035 at a speed-length ratio of 0.8; 0.017 at 1.2; and 0.080 at 1.8, a general variation roughly of the form $R/W = 0.009 (V/\sqrt{L})^{3.5}$.

^{*}The ratio V/\sqrt{L} is referred to as the "speed-length" ratio. V is in knots (1 kn = 1.15 mph) and L is the waterline length of the vessel in feet.

The form of displacement amphibian hulls has been so poor, and so befouled by appendages, that the rapid increase in wave-making resistance at higher speeds is not as apparent as in boats. Model tests of the WWII DUKW show the relationship $R/W = 0.053 (V/\sqrt{L})^{2.1}$; the WWII LVT, $P/W = 0.031 (V/\sqrt{L})^{2.2}$ [Nuttall and Hecker, 1945]. Tests on a simple, square-edged box of the same general submerged proportions give $R/W = 0.04 (V/\sqrt{L})^{2.0}$ [Kamm, 1966]. At reasonable operating speeds (say $V/\sqrt{L} = 1.1$), the specific resistance of the DUKW is six times, that of the LVT more than 3.5 times, and that of the box 4 times the specific resistance of a boat. In practice the maximum speeds of displacement amphibians have not exceeded $V/\sqrt{L} = 1.5$, and operating speeds are more usually in the range of 1-1.2.**

Note that while resistances increase as V^2 - V^3 , towrope power required increases as V^3 - V^5 , and installed power often still faster, because of deteriorating efficiencies of practical sized propellers under the excessive higher loadings forced upon most amphibians by limited dimensional envelopes which in turn limit possible propeller sizes.

And the problem is made still more intractable by propeller efficiencies. Where there is space within the design envelope for a proper size propeller,

*In dealing with amphibians and floaters, it is usual, and adequate, to use the overall vehicle length for L rather than the waterline length in forming the ratio V/\sqrt{L} .

**Even if higher power were supplied, considerable redesign would be necessary to prevent their swamping in their own bow waves at speeds much higher.

with clean flow to and from it, as on a good boat, the overall installed gross engine power-to-torque horsepower efficiency (or propulsive coefficient) is generally of the order of 0.4-0.6. On propeller-driven amphibians, it is rarely half this, often still less. The situation is not fundamentally changed when a high-speed water jet system is substituted for the conventional propeller(s). If, as has often been the case in the past, the total jet area is substantially smaller than the disc area of the propeller(s) it replaces, propulsive efficiency will actually be worse.

Simpler alternatives to the use of screw propellers, such as track or wheel propulsion, are usually far poorer [Witney, 1955; Cleare, 1963]. The situation is illustrated by examining the effective overall resistance to weight ratio (R_o/W) for a number of existing amphibians. This may readily be calculated from published installed horsepower, maximum speed, gross weight, and overall length figures. With only minor loss in precision, the calculated values may be organized into a simple pattern such that

$$R_o/W = K (V/\sqrt{L})^2 .$$

Approximate values for K for various types of propulsion and hull are shown in Table XI. The figures of Table XI, taken with the previously quoted figures on towrope resistance, indicate approximate values for propulsive coefficients for various general modes of propulsion as follows:

propellers	PC = 0.15-0.25
special water-	
propulsion tracks	PC = 0.10
normal tracks, tires	PC = 0.02-0.03

All of which is not to say that water speeds in excess of about 10 mph are impossible. Several possibilities do exist for substantially higher speeds, at a price. If the machine is designed to plane in the water, with wheels retracted out of the water flow, the propeller made retractable (to be stowable out of harm's way for land operations, but effectively placed for water operation), and a clean planing hull fitted, calm water speeds in the range of $V/\sqrt{L} = 3-6$ may be obtained at specific drags (R/W) of 0.16-0.20 [Kamm, 1966]. The effective drag ratio (R_o/W) of the Navy 5-ton 4x4, 1500 HP, gas turbine, planing amphibian is 0.5, indicating a propulsive coefficient of 0.35-0.40 [Shuships, 1962].

TABLE II

EFFECTIVE OVERALL RESISTANCE TO MOTION
IN WATER OF DISPLACEMENT APPROXIMATE

$$R_o/W = K(V/\sqrt{L})^2$$

<u>Propulsion</u>	<u>Hull</u>	<u>K</u>
Propeller	Rough ¹	0.3
Propeller	Clean ¹	0.2
Special Tracks ²	Clean	0.3
Normal Tracks ²	Clean	1.2
Wheels	Clean	2.9

¹"Rough" = hulls extensively cut up for wheels, axles, drive lines, etc., as on the DUKW and its immediate successors.
²"Clean" = similar to the LARC's with fewer cut-outs, fewer wheels, close fitting wheel wells made possible by elimination of the suspension, etc.
³"Special Tracks" = tracks designed specifically for effective water propulsion, as on the LVTs.
⁴"Normal Tracks" = land tracks as on the M13, M16, etc.

If the additional mechanical and control complications of hydrofoils, retractable for land operation, are added, the same speeds may be achieved with less drag at speed, and hence less power. The Navy's 5-ton 4x4, 1100 HP, gas turbine, hydrofoil amphibian operates at an effective drag ratio of 0.26, implying a flying drag of the order of 2.13, and a propulsive coefficient of about 0.5 [Buships, 1954]. "Take-off" drag, however, will be 50-150 percent higher [cf. Kamm, 1966], depending upon the refinement of hull design and whether or not the wheels are retracted. This high "hump" drag necessitates use of a variable propeller configuration for effective operation under high thrust at low speeds ($V/L = 2$) during take-off, and efficiency under lower thrust loads at higher speeds while flying. A major advantage of the hydrofoil configuration is that it can maintain high speeds in 2-3-foot seas which would force the planing hull to back off considerably.

Both approaches are costly, in dollars, in complication, and in weight. Both experimental types, despite the use of lightweight power plants and aluminum hulls, and the fitting of only marginally mobile land running gear, have a payload/gross weight ratio of only 0.26. This compares with ratios of the order of 0.4 for current, less exotic machines such as the LARC's, which in turn have already paid a 5-10 percent direct weight penalty for their amphibious features.

A third available alternative is to design displacement amphibians for use coupled in trains for long water hauls. Scale-model tests have shown that simply coupling eight elements reduces the unit drag so that, if equal propulsive

efficiency is assumed whether running singly or coupled, the operating speed of the train may be about double that of a single unit with the same installed power in each vehicle [Kam, 1966].

While the various figures quoted are historical, they are also in general accord with the current theory and practice of naval architecture. They make it clear that a specification for a water speed which is outside the state-of-the-art of amphibians must either be ignored, or allowed to govern the entire design. When, as has sometimes been the case, the specification is beyond good boat practice, it is patently ridiculous.

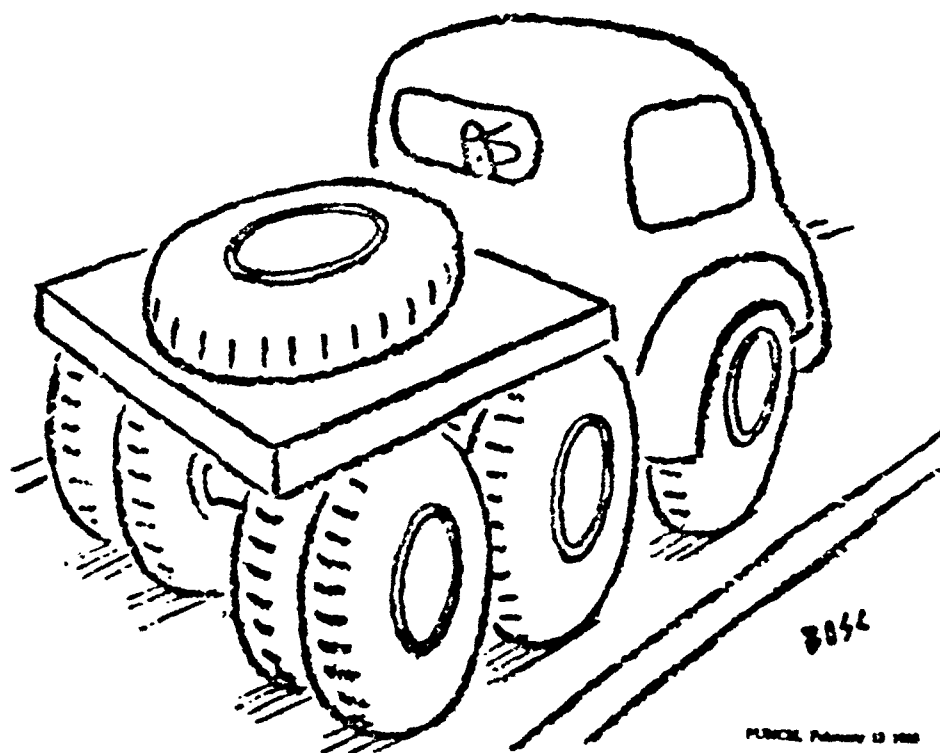
The bank access problem is also governed by fundamental considerations. First, the stream bed or canal ditch and its banks often constitute a formidable obstacle to even the best ground-crawling machines purely because of their geometry -- steep slopes, high vertical steps, etc. The problem is confounded by the fact that the soils on the steep banks are wet, making them slippery at best. Where the bank slope is inviting, the soils will often be very weak, waterlogged silts, etc. This basically difficult situation becomes still more so when the vehicle is afloat, or partially afloat, so that its maximum possible tractive thrust and the ability to bull through on momentum are both greatly reduced. Accordingly, there is far more to creating a viable river-crossing "floater" than simply adding buoyancy to an ordinary vehicle of already limited off-road mobility [cf. Wisner, 1965].

It appears probable that a reanalysis of the cost versus the true effectiveness of the current crop of floaters in the light of recent experience would show that most of them are not really justifiable at their present level of water and gross performance. Either more must be spent (in all coins) on their water and bank mobility or the requirement changed, perhaps back to deep fording capability; i.e., the current balance may well prove to be the point of least return.

A Mobility "Hot Rod"?

The design and construction of off-road vehicles has been a grim, prosaic business, largely unenlivened by the sporting element of outright performance competition, divorced from workaday problems of cost, reliability and a paying job to be done, which has from time to time benefited other spheres of transportation engineering. Such exceptions as the long-standing British off-road "trials" competition [*cf. Motor*, 22 Jan 1966], the annual Naples, Florida, "swamp buggy" race [*cf. Warner*, 1966], growing interest in sand dune racing [*cf. Sports Illustrated*, 10 Jan 1966], and cross-country racing in the USSR [*Motor*, 20 Aug 1966], have not yet produced any new knowledge and serve rather to point up the case.

It appears possible that a useful exercise at this juncture would be specifically to develop one or several different "mobility hot rods," to synthesize the effects of such competition. The proposed hot rods would be designed solely to carry an intrepid driver, a first-aid kit, and a minimum of lightweight, compact instrumentation at the highest possible speeds across a wide variety of difficult cross-country terrain. If cost/effectiveness and all other constraints which are now thought to limit the free application of current know-how could once be eliminated, and MOBILITY only made the object, the resulting machines would presumably represent the pinnacle of the state-of-the-art, against which the mobility of all current and proposed working machines could be measured. A serious, properly



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financed effort of this sort would answer many questions in a way that cannot be done on a blackboard or in a computer [Knorr and Morgenstern, 1965]; in a way which can be readily grasped by everyone concerned with the problem, from top to bottom.

While it does not appear likely, the hot rod performance might just turn out to be disappointingly little better than that of our current good machines. This is a risk the vehicle-terrain research community should take, even though it could force them into new and more promising lines of personal endeavor. If, however, the current upper limit could be demonstrated in metal to be substantially better than the few percent improvement which is regularly promulgated by advocates of more and more reliance on air transport, it could develop a demand for the rebalance of design priorities thought to be needed to make real progress in cross-country mobility. It would also generate requirements for more and better research. In either case, everyone would learn much. And it would be fun.

Specifying Performance

In the official system, the development of a vehicle begins with the same sort of specifications of performance and other features which go into the QMR. The complete specification deals with many problems and features, of which off-road mobility is only one. Others are:

- 1) reliability
- 2) effectiveness -- combat load or cargo, armor and firepower or tonnage, speed, and vulnerability
- 3) transportability, which today means, increasingly, air transportability
- 4) transport efficiency, which is primarily concerned with fuel consumption and with logistic support required
- 5) durability
- 6) maintainability
- 7) manpower requirements in terms of numbers, training, and general intelligence level

Each of these characteristics is covered in a number of different ways. Some, such as reliability, durability, and maintainability, have proven to be almost as nebulous and difficult to specify as mobility. There is a current healthy trend towards specifying all requirements in functional terms, leaving means to the designer. Some redundancy or "overspecification" still occurs, however, which often serves as an "out" for the designer when the functional requirements cannot be met.

In relation to mobility or off-road performance, specifications are currently stated in four general ways, none of which are truly quantitative and hence acceptable:

1) Performance may be expressed in terms of equivalence to a known vehicle. A specification may read that "the mobility (of a new vehicle) . . . should be equal to that of the M4V2." Since no definition of equivalence is given, this in practice reduces to identity. For example, a question was raised at a 1964 bidders' conference as to whether a 3-wheeled vehicle would be acceptable. The answer was "No." The reason? There would be no way of knowing whether the mobility of a 3-wheeler was in fact equivalent to that of the comparison vehicle named in the specification, which had four wheels.

2) There is a plethora of happy qualitative terms: "maximum mobility," "optimum mobility," etc., all undefinable in quantitative terms. They are not specifications but rather king-size loopholes.

3) Requirements are sometimes stated in terms of simple indices which relate to mobility in a general way, such as nominal unit ground pressure (NUGP) and horsepower per ton (HP/T). While better than nothing, these are a long way from testable performance specifications.

4) The specification may spell out a number of other arbitrary design features and characteristics sometimes based upon an overall problem analysis. These may include angles of approach and departure, ground clearances, widths, swimming configuration, etc., in addition to the indices in (3) above. An example is the excellent study "Logistical Vehicle Off-Road Mobility" prepared by the Transportation Combat Developments Agency, Fort Eustis [Brown, 1963]. Figure 16 reproduces the tabulated results of this study. The difficulty with this type of specification is that because of the interrelationships between nominally independent features, it in effect designs the vehicle in all except detail without regard for alternative mechanical possibilities for overcoming various types of terrain-vehicle problems.

In addition there are some "unfortunate specifications which involve samples of all types of the above. It should be clear at this late point in the discussion that the inclusion of unnecessary constraints and conditions reduces, sometimes to the vanishing point, the degrees of freedom left to the designer in reaching a solution [Tuttle, 1964]. Too many vehicle CMR's present the design agency with what is effectively a completely frozen design [Schlepper, 1964].

The basically nebulous specification of mobility and off-road performance is all too frequently in contrast to the detail given in other areas. There is a natural tendency to adhere to closely specified requirements (except -- by some unstated convention -- weight) at the expense of those less well stated, regardless of a pious list of priorities.

The need for quantitative off-road performance specifications has been recognized before now [cf. Liston, 1964; Shiovitz, 1964]. Of course, to have meaning, to be testable, not only must the performance be called out in measurable, engineering terms, but the relevant terrain conditions must also be specified, again in measurable engineering terms. And most important, and difficult, the specifications must present the minimum performance which will satisfactorily do the job where it must be done.

Such realistic specifications can only come as the result of careful analysis of the mission and of the terrain, including the development of a viable operational doctrine which outlines the way in which the equipment is to be used in specific

difficult terrain situations and the performance limitations which have been accepted in the design from the outset. Asking for more than is reasonably required can only lead to tacit agreement that the specifications may be ignored, and to a return to the present unsatisfactory state of affairs.

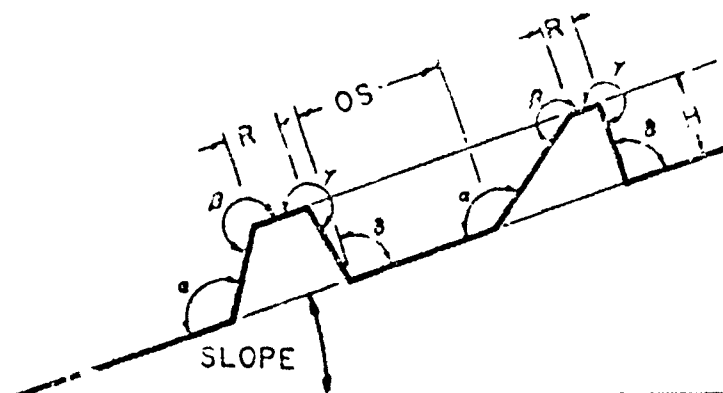
A fully useful, testable off-road performance specification will consist of a matrix of several (perhaps many) measurable performance versus measurable terrain feature relationships. There is already broad agreement upon the list of terrain-vehicle interactions which govern off-road mobility, and hence of the factors which should appear in a proper specification matrix. The list is deceptively simple, and fully coincident with the areas of terrain-vehicle research outlined in an earlier section. Terrain features which affect vehicle performance are [cf. TECP 700-700, 1964; Grabau, 1965; VMEA, 1965; Wisner, 1965; MERS, 1966; Liston and Hanamoto, 1966; Shawburger, 1966]:

- 1) the mechanical strength properties of the surface material system, including layering effects;
- 2) the surface geometry, including slope, discrete geometric obstacles, and continuous roughness;
- 3) vegetation spacing and mechanical impedance; and
- 4) water barriers, including the land/water interface geometry and composition, geometry of the cross section and current velocities.

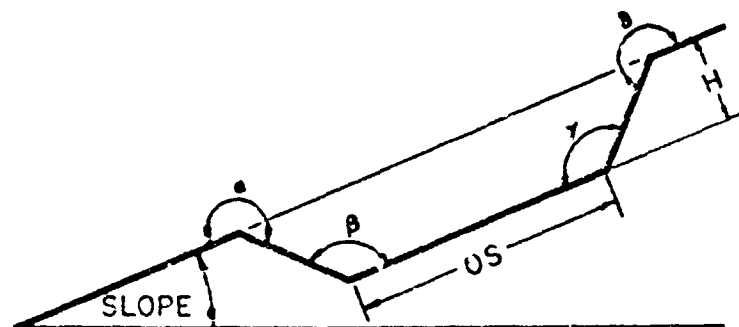
This system of geometric terrain measurements utilized in the MERS studies is illustrated in Figure 17. It is recognized that these several types of terrain features will often act in concert. However, analysis indicates that the critical combinations are generally only those involving weak surface materials [VMEA, 1965].

The important primary vehicle response is in all cases simply its practical operating speed, which in severe conditions, as in negotiating near limiting obstacles, reduces to "0 or >0," or the familiar "go" or "no-go" criterion. In some instances, particularly in the case of operation over rough terrain and subcritical obstacles, the "practical" operating speed requires definition in terms of acceptable vehicle response, such as PSD, amplitude, acceleration, and/or jerk limits at various critical locations in the vehicle.

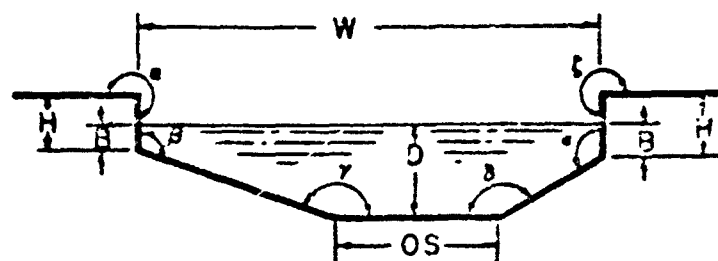
Recent tests have demonstrated that, as earlier suggested by Jones [1955], in many subcritical terrain situations a vehicle's practical maximum operating speed is more strongly influenced by the driver's experience, physique, temperament, and élan; by details of control and cab arrangement; and by vehicle responsiveness to control, than by the fundamental vehicle characteristics with which terrain-vehicle research has dealt [Liston and Hamamoto, 1956]. While this is surely an area for further investigation, solutions should not be attempted in the specifications. Rather, the specifications should include performance trials which involve only the vehicle components of the problem -- cab and controls and responsiveness. The driver variable should be minimized in such tests by using only experienced, capable drivers after they have had ample opportunity to become familiar with and confident in the vehicle. After all, the road test results on automobiles, regularly published in *Motor*, *Popular Mechanics*, etc., are not run by just anyone's grandmother. They represent the best that an especially qualified driver can do with the vehicle, and thus



a OBSTACLES



b. DITCHES



c WATER BARRIERS

Fig. 17. A scheme for obstacle quantification

become a useful and repeatable index of its intrinsic limiting performance.

A somewhat simplified preliminary sample off-road performance specification matrix is presented in Figure 18, for illustration only. It does not represent any real problem or terrain, and covers only off-road performance characteristics. In concocting this sample, the opportunity was taken to indicate that the variation in required characteristics with terrain severity need not follow the same trends as do those of any one vehicle, with the result that in order to meet the specifications, designed performances in some areas may be in excess of those required, as a result of steps necessary to satisfy requirements in others. The same information could be presented in the form of curves and families of curves. The concept of the matrix presentation is that, by and large, points of probable controlling importance are given rather than the complete spectrum.

SAMPLE OFF-ROAD PERFORMANCE SPECIFICATION MATRIX

1. Deep Soil Performance

1.1 First Pass

1.1.1 Five Trained Tests

Stage 1	W ₁	C ₁	Speed, mph
1	10	1.0	10
2	15	1.5	15
3	20	2.0	20
4	25	2.5	25
5	30	3.0	30

1.1.2 Tests

Stage 2	C ₂	Speed, mph
1	1.0	10
2	1.5	15
3	2.0	20
4	2.5	25
5	3.0	30

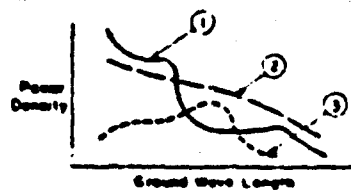
1.2 Multipass Trafficability

W₁ = 15

2. Rough Terrain Performance

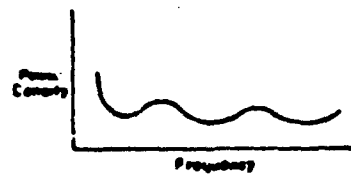
2.1 Terrain 1 Max speed, 10 mph

Power	Locality
1	20
2	45



2.2 Constraints

- a) Maximum acceleration at driver's seat: 0.8 g
- b) Maximum power density at driver's seat



3. Geometric Obstacle Negotiation: Go Performance

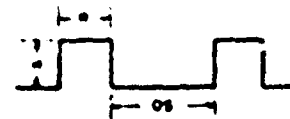
3.1 Slope

W ₁	W ₂	W ₃	C ₁	C ₂
10°	10	1.0	1	1
15°	15	1.5	1	1
20°	20	2.0	1	1
25°	25	2.5	1	1
30°	30	3.0	1	1
35°	35	3.5	1	1



3.2 Ridge

W ₁	W ₂	W ₃	C ₁	C ₂
10	10	1.0	1	1
15	15	1.5	1	1
20	20	2.0	1	1
25	25	2.5	1	1
30	30	3.0	1	1



3.3 Pits

W ₁	W ₂	W ₃	C ₁	C ₂
10	10	1.0	1	1
15	15	1.5	1	1
20	20	2.0	1	1
25	25	2.5	1	1
30	30	3.0	1	1



4. Vegetation Negotiation

4.1 Stem Diameter < 2"

Average Stem Spacing, ft.	Speed, mph
1	10
2	10

4.2 Stem Diameter > 2"

Average Stem Spacing, ft.	Speed, mph
1	10
2	10

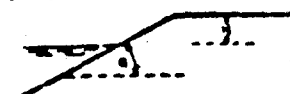
Water Operation

5.1.1 Water Speed: 1 mph

5.2 Bank Negotiation: Go Performance, Ingress & Egress

5.2.1 Sloped Banks

W ₁	W ₂	W ₃	C ₁	C ₂
10°	10	1.0	1	1
15°	15	1.5	1	1
20°	20	2.0	1	1
25°	25	2.5	1	1
30°	30	3.0	1	1



5.2.2 Vertical Banks

W ₁	W ₂	W ₃	C ₁	C ₂
10	10	1.0	1	1
15	15	1.5	1	1
20	20	2.0	1	1
25	25	2.5	1	1
30	30	3.0	1	1



Fig. 19

Checking Performance

A prototype is currently subject to a wide variety of tests by numerous organizations. It is tested by its builder, demonstrated and briefly checked by the developing agency, and formally tested by AMC's Test and Evaluation Command (TECOM) at Aberdeen Proving Ground and at various of their field stations. It may go on to be loaned to various interested user boards and field groups, and a few copies may be put into the hands of troops in the field.

Some recent contracts have called for fabrication of and limited testing of "test rigs" prior to building prototypes for formal testing. While on the face of it, this adds time and dollars to the process, it in fact saves both, by allowing the contractor and development agency to check-out and debug the design before submitting it to the rigors of the complete test regime. The vehicles which do go out for TECOM testing thus may be "second generation" exemplars, with a greatly improved chance of survival [Sissom, 1965; Morrison, 1965].

Once the vehicle is released by the developing agency, further testing is now primarily the responsibility of TECOM, whose aim is to provide sound, objective, timely, impartial, and independent evaluations. The complete TECOM test program may take over a year, and, for a typical cargo truck, will include engineering tests at Aberdeen Proving Ground (APG), tests by the Armor Board and Transportation Corps, and tests in Arctic, tropic, and desert environments [Sissom, 1965].

The tests at APG will be concerned with performance, durability, reliability, maintain-

ability, transportability, vulnerability, safety, and human factors. The attempt is made to determine adherence to the original QMR's, and recently has further been complicated by the need to obtain data for determining awards and penalties under contracts having incentive clauses for the achievement of specific objectives. The opportunity is also taken to develop data for use in future design work [McNeil, 1965].

The fundamental weakness of the system from a mobility viewpoint appears to be that the designer and the test agency each must make their own interpretation of the QMR; the one to engineer the design, the other to devise and conduct tests [Sisson, 1965]. The built-in dangers of this are all too apparent. Proper testable off-road performance specifications would, of course, make the basic procedure in relation to engineering tests of mobility more rational, and also, incidentally, make them more difficult to perform.

The same problem arises in field tests of various kinds. The testing group must interpret the QMR in operational terms which may or may not turn out to be the framework within which the vehicle was conceived. Computer technology has dramatized the fact that an operating system consists of both hardware and software. In the off-road vehicle context, the vehicle is the hardware, and the software is the operational concept by which the hardware is conceived to be capable of handling the stated problems.

As a simple example, analysis of one complete problem, including overall cost/effectiveness, may dictate design of a machine which can operate under

some circumstances only at the half rated load, under others only by fitting chains, etc. The testable specifications would be drawn accordingly, and, if the design technology were adequate, the resulting vehicle would indeed not be able to operate in the stated conditions without these aids. It would, accordingly, be patently ridiculous to fault the vehicle for this lack of performance, and yet if this operational concept were not forwarded with the test vehicle, as part of the system to be tested, the testing agency could well become annoyed by the vehicle's apparent shortcomings.

Throughout current testing programs, the mobility of a vehicle will be tested by means of drawbar pull-slip tests in a small number of simple soils [TECP 700-700, 1964], and its performance will be qualitatively observed on a number of available "cross-country" courses. It may be submitted to WFS for trafficability testing [cf. Rush, 1962]. Comparisons may be made of the results to observations on other similar vehicles, and to whatever level of mobility specifications were initially provided, but as of the moment, there will be few meaningful numbers. Many results will be highly subjective, varying from enthusiastic (project officer, builder's public relations officer) to cool (blast test personnel who have never seen the vehicle they could not stick, or break up). The mobility of a given vehicle usually differs in the opinion of each observer according to his overall vehicular experiences, his basic objectivity, and the environments in which he has seen the vehicle operate. More often than not his opinion is influenced by

the apparent frequency of immobilizations he has observed, without regard for all circumstances or for relative performance levels in "go" conditions.

In an effort to lay the groundwork for more realistic evaluations of equipment mobility, a number of multivehicle field trials in natural environments were conducted in 1961-1963. The field conditions were selected to represent broad climatic/environmental areas: the tropics, the desert, the arctic and subarctic in both winter and summer, and temperate areas [Swamp Fox I, 1963; Wheel Track, 1963; Bog Busters, 1963; Harrison and Bischoff, 1963; Swamp Fox II, 1964].

The tests were of two general types, exemplified by Swamp Fox I and II, respectively. In the first, the test vehicles are operated in performance of a sample mission. In Swamp Fox I this was to proceed over the general route of the as yet uncompleted section of the Pan American Highway from Chepo to El Real in the Republic of Panama. In the second type of tests (Swamp Fox II, for instance -- also in Panama), the vehicles are operated and/or tested over relatively short courses in the vicinity of a base camp. The courses are selected to represent various types of conditions found in the general area.

The concept of examining vehicle mobility in the total environment context is sound, provided that the objects are sufficiently modest and clearly stated. In particular, much can still be learned from mission-type exercises involving

homogeneous,* compatible* fleets of developed military vehicles. Both the environment and the vehicles and operational concepts are tested by such an operation. The test areas should, however, be previously examined by multidisciplinary environmental teams and classified, insofar as feasible, by all available means, including those based upon mechanical measurements. Members of the same teams should accompany the exercise to observe and record results and interactions, but should not expect to collect extensive environmental data during it.

*A group of vehicles (of various types) may be said to be *homogeneous* when each type has approximately the same general performance level in a number of different terrain types of interest. It is evident that if one type of vehicle assigned to an operating unit is significantly less mobile than the rest, the operation must be geared to its low performance level.

The various types of vehicles within a group may be said to be *compatible*, from a mobility standpoint, when they can be used over a given path in the terrain types of interest essentially in any order. This is more easily understood by considering two machines which might be included in a homogeneous fleet, as defined, but which would nonetheless NOT be compatible. Two such, approximately, would be a good "GOER" and a recent "jeep." While both might just negotiate a given virgin stretch of soft ground (and would hence constitute a homogeneous fleet for this particular terrain), the jeep would usually be unable to do so after the GOER had made its pass or passes, leaving large ruts and a vastly destroyed terrain. The GOER's performance, on the other hand, would be generally unaffected by prior passage(s) of the jeep. A similar situation could develop in lightly wooded areas, where the jeep might readily thread its way through first, but might have extreme difficulty negotiating the stumps and fallen trees in the wake of the larger machine [Nuttall and Cohron, 1964].

We are still not to the point where careful, direct, comparative evaluation of a large number of widely different vehicles can be anything but instructive. This type of program is best conducted in a base-camp type of operation. It probably need not be done in especially remote areas. Adequate analog situations can be found or created for most of the significant terrain features of an environment in relatively accessible locations, if these features have been determined and adequately described and measured by competent environmental survey teams. Base-camp multivehicle evaluations which for some special reason (such as cadre training) must be conducted in remote natural environments should be thoroughly planned well in advance on the basis of sound environmental data. These must include both general coverage of the broad area of interest, and the very particular information necessary for the selection of valid test courses.

The problems of evaluating the mobility of a number of different vehicles by means of direct comparative field testing are more complex than might at first appear. The environmental viewpoint does not, by itself, guarantee meaningful results. Sensible vehicle test techniques, knowledgeably applied, are also required. Obviously these are not matters which can be left to take care of themselves in the field. The entire exercise, from planning, through conduct, to its wrap-up in meaningful evaluations of and generalizations on the vehicles and environments involved, requires a breadth of viewpoint and competence which is just developing.

SYSTEM ANALYSIS

"An early victim of any prolonged peace is military reaction. It happens in every system. The hard truths of the battlefield, indelibly imprinted on the minds of leaders who learn by experience, are too soon diluted by their successors, who know their subject only in theory."

- Marshall, 1966.

The point has been taken that off-road vehicles, and ground-crawling machines in general, are an old business even though study of their off-road performance within a formal engineering framework is not. Progress made in the past 25 years, both in the development of the technology and in the production of practical vehicles, whether sired with the blessing of formal technology or not, must be judged in this context. It is not properly gauged against the newer, more glamorous engineering fields but rather against the progress of the automobile itself, progress in structural design, ship work perhaps, and in other similarly mature engineering areas. Moreover, as in these other mature areas, off-road vehicle progress has in part been the result of improved general understanding of the problems *per se*, the availability of better materials, and the overall advance of all technology, as well as to the march of its own particular technology.

So judged, the practical advances of the past 25 years appear acceptable if not exciting. There have been no "breakthroughs," either in the research or in practice. As a matter of fact, one of the major results of terrain-vehicle research has been the clear indication that there probably

will not be any breakthroughs, no magic solutions, but rather only continuing modest year-by-year gains. This is to be expected in a mature field and does not necessarily reflect upon the quality of the research. Breakthroughs may, probably will, occur in the general field of off-road transport, but they are unlikely to come from research which is focused solely upon ground-crawling. When a breakthrough does come, it will come from work essentially unrelated to study of the intimate relationships between the ground and a vehicle. Advanced ground effect machines, or still more reliable and effective helicopters, for example, may ultimately prove to be the best solution to the general off-road problem, but such solutions will lie outside the envelope of limitations, real and arbitrary, imposed upon ground crawlers by physical laws, by the state-of-the-art in supporting technologies, and by economic considerations. Thus, the search for increased ground mobility in our military vehicles must rely essentially upon better exploitation of available technology and on the demonstration (if it is true) that the currently accepted balance of conflicting requirements which limits that exploitation is not optimum for the new jobs which must be done. This is a systems analysis job. It is naïve to believe, however, that such analysis can improve the situation by anything like the order of magnitude that a true "breakthrough" might achieve [Hitch and McKean, 1965].

It is also naïve to believe that our current vehicles do not already represent a high degree of optimization. This has not been achieved by

formal means, but the vehicles we have are the result of a kind of marketplace optimization, a consensus of experienced and responsible people as to the proper compromise between what is desirable and what is technically and economically feasible. The term "universal" vehicle has been widely used to derogate earlier efforts at reaching an optimum military machine. The failure of standard military vehicles to negotiate one or another difficult stretch of terrain is frequently cited as the result of accepting a "universal" answer. Clearly any machine, optimized upon any basis except the achievement of absolute maximum mobility, will sooner or later encounter similar embarrassing situations. This is the nature of optimization.

The crux of the matter appears rather to be that current vehicles are optimized, perhaps most often unconsciously, but sometimes, as in the case of the MBT70, deliberately so [Watson, 1966; Shiovitz, 1966], for the type of terrain and type of operations which are currently anticipated if war comes to Europe. It may be said that the current vehicles are optimized to a high degree for European operations as foreseen by our military establishment.

Our present concern arises from the fact that we now recognize the need for machines to operate in areas of the world which are quite unlike Europe, climatically, ecologically, culturally, etc.; areas where our "European family" of vehicles is obviously far from optimum, often totally useless. These are not isolated spots or small areas requiring "special purpose" vehicles, but extensive segments of the globe where the difficulty

is ambient, and where our best standard vehicles, even when functioning, do so too close to the ragged edge, too much of the time.

The true problem which confronts us is not to develop a scattering of weird "special purpose" vehicles and toys, but rather a whole new family of working vehicles, designed and optimized for these significantly different and more difficult conditions, and to do so far more rapidly than was done in the past by trial and error for our present European family. This too is properly a systems analysis job.

The total systems approach must of course include such things as strategy, logistics [of. Gay, 1964; Vassar, 1964; Kulp, 1965], dollar costs [of. Heymont, 1965], doctrine, and total operational concept [of. Howze, 1961]. It must include alternatives to off-road vehicles [Philippe, 1964; VNEA, 1965], including aircraft [of. Humes, 1965], and various levels of engineer or air support of vehicles having lesser degrees of off-road mobility than may from time to time be needed [of. Kerkering, 1964, 1965]. Assuming that a study involving all of these elements still dictates significant roles in these geographic areas for off-road vehicles, then these roles must be specified quantitatively both in terms of the job to be done and the terrain in which that work must be accomplished. It must also either assume or develop a generalized value system in which dollar costs can only be one factor. To be realistic, both the mission profiles and the value systems will still have to be spelled out in relatively broad terms because, although theoretically possible, it is in fact inconceivable

for the military to have a separate vehicle tailored to every new situation.

The systems analysis must be supported by valid terrain-vehicle relationships and models and by adequate, pertinent terrain data translated or at least translatable, into the specific engineering values needed in the terrain-vehicle relationship models. Means for acquiring and presenting such data have been demonstrated in the MERS program and there is already a growing body of useful data [cf. Pula et al., 1963; Mills and Clagg, 1964; Kennedy and Rush, 1965; Leighty, 1965; MERS, 1966; Rojanasoonthon, 1966; Sloss and Lassaline, 1966; Cassett et al., 1966] on specific problem areas, both geographic and technical. Means for generalizing this type of data are also under study [Heldridge et al., 1966].

Systems analysis must also have available the generalized state-of-the-art in vehicles and components and include full consideration of other militarily important factors -- such as durability, reliability, and maintainability -- which have rivaled mobility as elusive concepts to quantify.

Of all of these, perhaps the question of the ultimate trade-off value system is the most perplexing. Indeed, this is the "hardest part" of operations analysis, which as a science has made great strides in analyzing naval and air warfare, but is still "far from having a good grasp of ground operations" [Hazelwood, 1966]. In commercial operations, dollar cost is paramount and the elements of cost to be considered can be easily specified. In military operations, on the other hand, the value of a few miles-per-hour gain

in speed, a few miles shorter route, or a few percent less likelihood of bogging cannot actually be reduced to dollars and cents, although indirectly this is in effect done regularly.

Many of the elements of systems analysis as applied to off-road vehicle operation have been tackled [cf. Peterson, 1957, 1958; Bekker, 1958; Davis, 1959], and its feasibility as a preliminary to off-road vehicle design has recently been demonstrated in several published studies [cf. Moss, 1954; Bekker and Butterworth, 1964, 1965; Ehrlich et al., 1964; Fielding, 1964; Sutton et al., 1964; Mettam, 1964].

There is no question but that, with the proper degree of realism and accuracy both in the models and the input environmental data, the development of sound vehicle design targets can be done rapidly by this route. It bears stressing, however, that the answer will be little better than the concept and realism of the complex mission profiles used, the accuracy of terrain-vehicle relationships used, and the adequacy of the environmental data used. Note that these represent three distinct types of research results -- operations research, terrain-vehicle research, and environmental research.

Granted then that the systems analysis as a part of ground vehicle design is feasible, desirable, and needed at this moment, how should it be implemented? Where does it fit in the overall design procedure? Who should do what?

The broad systems analysis which considers all alternatives, including ground-crawling machines as only one, which includes strategy and

doctrine considerations, and which formulates the overall mission profiles, is clearly an operations analysis function. Parametric engineering design studies and detailed engineering design are as clearly the responsibility of vehicle engineers. There is a gray area between. This is the essential link between the two, the cataloging of the absolute minimum of mechanics' constraints on, and the reduction to quantitative engineering terms of the performance-terrain matrix required of, the new vehicle if it is satisfactorily to match the mission requirements. This is a formidable assignment. It appears, however, to be more nearly the function of an operations analysis group, perhaps an "interpretive" operations analysis group, than a part of engineering design.

The vehicle performance-terrain matrix in engineering terms becomes a testable specification which the vehicle engineer can use as the framework for parametric engineering studies and subsequent detailed design. When the vehicle is offered in metal, it becomes the basis for judging the success with which the vehicle engineering has been achieved, and automatically designs the first round of tests to which test beds and prototypes are subject. The adequacy of the testable terrain-performance matrix itself should subsequently be determined by field testing within the scope of the operational doctrine developed by the initial operational analysis.

Some such clear division of labor would accomplish a number of salutary things. First, it would place responsibility for correctness of

the analysis of the operational situation with an operations analysis group who, in turn, would be forced to demand sound operations research models and methods, and adequate, valid, environmental data. It would place responsibility for the actual mechanical design of an optimum machine to meet performance specified in engineering terms wholly with an engineering group who, in turn, would be forced to demand valid, accurate, terrain-vehicle technology. And incidentally, it would get the engineers back on the drawing board where they belong, even though playing at geographers, ecologists, or hydrologists is evidently more fun.

ORGANIZATION FOR DESIGNABILITY

The current state-of-the-art of design of military vehicles is fundamentally weakest in the wandering organizational route by which a field requirement eventually becomes a vehicle ready for production. This committee-ridden process is characterized by a comingling of research and design, lack of job division along sound professional and functional lines, and partly as a result, lack of testable performance specifications, and hence of clear lines of responsibility for various aspects of the success of the final product.

This situation exists whether or not the problem is to develop a new "second family" of vehicles, the next generation of the current European family, or a single special machine. In every case, strengthening this procedure is essential to timely progress, including the accelerated generation of valid, responsible terrain-vehicle research results.

In relation to ground-crawling vehicles, the objects of any alteration to present design and development procedures must be to reduce the time required to respond to a valid field requirement, and to insure that the hardware developed does indeed meet it. Essential elements in a working system, lacking in the present process, are:

- 1) clear separation of research and development activities from the "requirements" design line; i.e., a development should not be undertaken in this line unless the complete requirement, once properly stated in quantitative engineering terms, is within current and realistically projected technology;

2) division of work of the requirements line along sound professional and functional lines with definable interfaces; i.e., operational analysts should not design vehicles, design engineers should not have to become geographers, etc.; and

3) assignment of definable responsibility to each functional group and means to measure its performance.

One simple and somewhat obvious organizational scheme which might meet the basic requirements is diagrammed in elemental form in Figure 19. Only the most important feedback and communications loops are shown. It segregates three separate lines of activity -- requirements design, components development, and terrain/performance research, the latter including the design, construction, and testing of mobility idea vehicles. The diagram illustrates their natural relationship, and a clear division of responsibility along functional and professional lines. The proposed realignment of responsibilities would not require a sweeping reorganization of the Army, or of its general development procedures. Rather, the proposal closely matches the current Army R&D organization. It envisions only certain simple but fundamental changes to assign clear responsibilities to various organizational elements, and in the process to limit the baleful influence of interorganizational committee irresponsibility.

The first division proposed in the requirements design line is to place responsibility for quantitative, functional vehicle specifications (only), to meet a new requirement, entirely with an operational analysis group

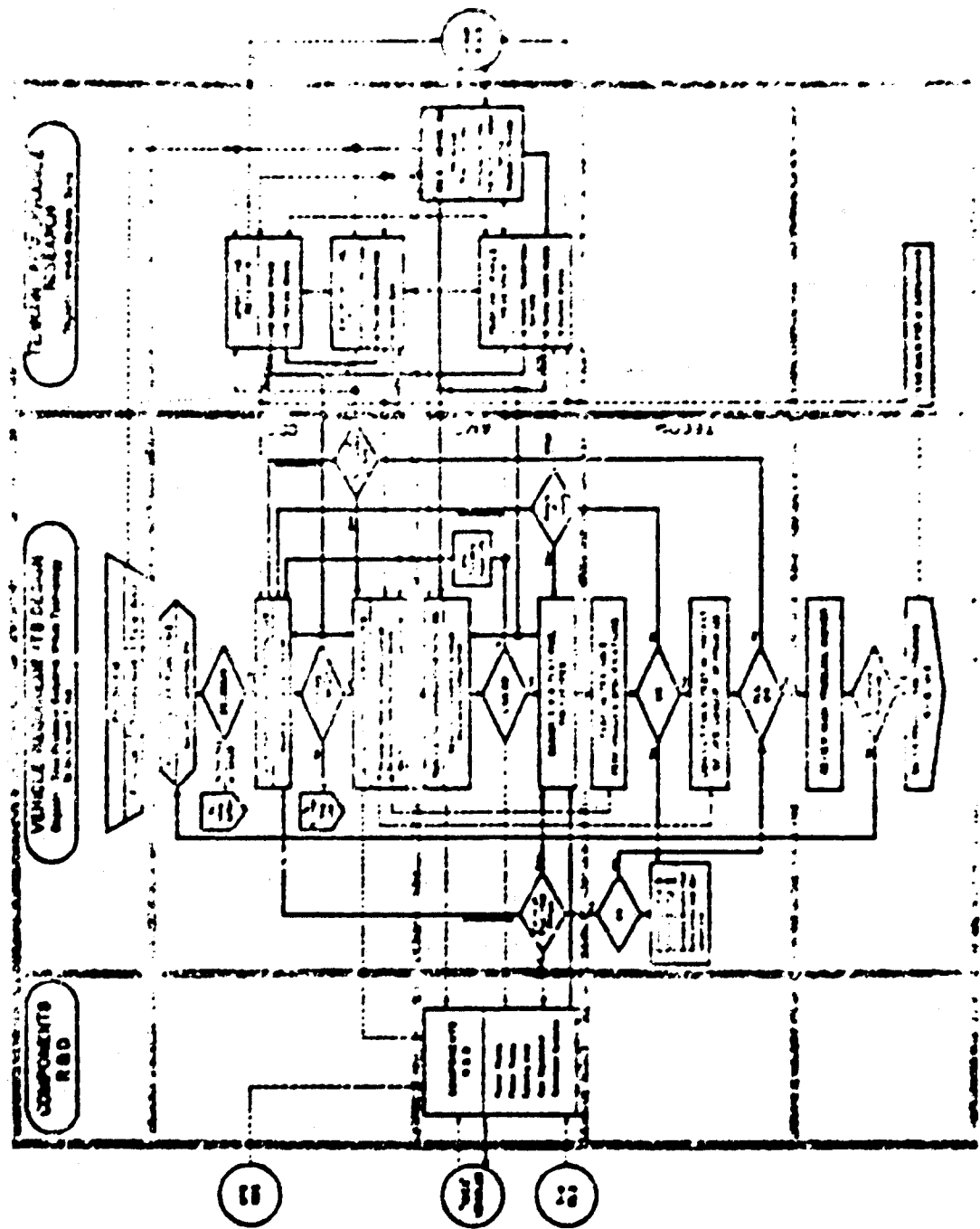


Fig. 19. Organization for reality

(perhaps within CDC). This group, in relation to off-road performance, would determine at the outset (if necessary) whether or not a ground crawling machine is called for. If so, by systems analysis techniques, it would develop an operational concept generally within the state-of-the-art, and specify the performance in testable engineering terms of the vehicle needed to implement this plan. An incomplete illustration of the type of performance-terrain matrix to be developed was given earlier in Figure 18. The operational analysis group would also be responsible for the development of an absolute minimum list of essential design constraints -- true maximum weight and/or dimensions as limited by helicopter lift, for example, maximum production cost if this has influenced their operational decisions, ambient atmospheric limits, special environmental problems such as fungus attack or corrosion which will be encountered, etc. -- and, where appropriate, minimum armor and armament performance features. The operational analysis group would not only provide the testable off-road performance specifications to which the vehicle designers would be held, but also be accountable for their adequacy in relation to the field job to be done by the finished vehicle.

In the off-road design context, all environmental research would accordingly become of interest primarily to this group. This group would also require the support of research to develop realistic operational models, to develop valid terrain models, and to develop generalized parametric information on the state-of-the-art in vehicle design.

The developed performance-terrain matrix, constraints, functional features, and the operational concept (the latter for information only) would be forwarded to the vehicle development agency (AVC), who would have sole responsibility for meeting in an optimum mechanical configuration the testable performance specifications within the given constraints, or for rejecting the job at the outset as beyond current technology.

If the vehicle engineers determine that the job as presented to them is feasible, they next develop the optimum mechanical configuration in more detailed parametric and engineering design studies, and proceed to design and fabricate test models with a minimum of further palaver. If they decide the machine called for is beyond the state-of-the-art, they return their studies with their analyses to the operations group, who may then either drop the matter (as a ground-crawling vehicle), move the project out of the requirements line into the R&D area, or, upon restudy, submit revised specifications in the same terms as before.

Terrain-vehicle research, elucidating the relationships between measurable terrain features and vehicle performance, would be conducted largely in support of the mechanical design effort. An essential feature of the terrain-vehicle R&D, currently lacking, would be its active participation in the initiation, planning, and testing of "ideas" vehicles, with the hoped-for result that more mobility ideas will become evident in their ranks than has been the case in the past.

Off-road performance testing of vehicles in the requirements line would be conducted at two

distinct levels, as now (TECCM). The first round of tests would be conducted entirely in relation to the testable performance specifications, and would determine whether or not these had been met by the design agency. These tests would automatically check the validity and accuracy of the terrain-vehicle relationships used in the design. If these showed the vehicle to be satisfactory, it would proceed to other engineering tests of primary importance and to field tests -- along with the operational doctrine within which the testable performance specifications were conceived. The field tests would be conducted according to the supporting doctrine and would determine whether or not the vehicle and doctrine met the original functional requirement. In the process, the field tests would check the validity and accuracy of the terrain and operational models used.

Such a system could be expected to provide faster and more reliable response to many field requirements for vehicles by separating R&D from the specific requirements design line, and by establishing quantitative specifications which limit the power of across-the-board committees of changing personnel to meddle constantly with the work in progress.

It could also be expected to restore a sense of responsibility to vehicle development contractors, who would, like the government design agency, be under the gun to meet truly testable specifications once they accepted a contract. And it should have a salutary effect upon all relevant research efforts. Having once been asked the right questions within the framework of a

properly functioning engineering procedure, and subsequently bounded by "feedback" from unforeseen field experiences, supporting research on operations, on terrain-vehicle relationships, and on the environment would be forced to operate in real time on real problems and to come up with real answers. And we could all shave more comfortably.

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APPENDIX III

INDEX OF THE EFFECTS OF PERFORMANCE INDICES

The labors of vehicle-soil mechanics for over twenty years have, not unexpectedly, repeatedly been concerned with means to predict the performance of wheels and tires in soils. The approaches have been varied and so, at first glance, have the results. Each system has its adherents, however, suggesting, since there is only one reality, that the differences may not be as great as they appear. Accordingly, it is instructive to derive from each an index of limiting performance, and to compare the results.

In the following exercise, the nominal unit ground pressure of a tire (or wheel) is arbitrarily defined as

$$\text{NUGP} = \frac{W_1}{b \cdot r} \quad (\text{psi}) \quad (\text{III-9.1})$$

where W_1 = the (average) gross load carried on a single tire (lb)

b = the undeflected tire section width (in)

$r = d/2$ = the undeflected tire radius (in)

1. The Ekland Mobility Factor

As a result of extensive tests during WWII, a series of guidelines for properly sizing the tires of military vehicles were drawn up and published by the Engineer Board [Ekland, 1945]. Considerations in tire size selection included normal (highway) and low pressure (off-road) operations from both ground mobility and tire economic viewpoints. The concept of an optimum load and inflation for a given size of tire in a given service was advanced, and a ratio developed to express actual tire loading in relation to the suggested optimum. In the years since, this ratio has been called the "Ekland Mobility Factor."

For present purposes the complete system may be represented by the equation for the load-carrying aspect only of a single load-inflation schedule, obtained by simple manipulation of the equations given by Eklund (which are basic to all of the schedules), as follows:

$$N_e = 100 - 50 \left[\frac{W_1}{1.6 d_r^{0.91} b^{1.95}} - 1 \right] \quad (\text{III-1.1})$$

where d_r = nominal rim diameter (in).

For a mobility index of 100, the optimum tire loading (at a corresponding inflation) is given by:

$$\frac{W_1}{d_r^{0.91} b^{1.95}} = 1.6 \quad (\text{III-1.2})$$

or

$$\text{NUGP} = 52 \left(\frac{d_r}{d} \right)^{0.91} \left(\frac{b}{d} \right)^{1.95} \quad (\text{III-1.3})$$

For conventionally proportioned tires ($b/d = 0.25 - 0.30$; $d_r/d = 0.5 - 0.4$) the optimum NUGP reduces to

$$\text{NUGP} = 0.454 d^{0.83} \quad (\pm 1.5\%) \quad (\text{III-1.4})$$

Note that simple dimensional reasoning would suggest that a family of similar tires would have similar performance in homogeneous sand terrain if NUGP were proportional to d , and in homogeneous clay terrain if NUGP were constant.

Over a modest range of loadings above and below the optimum, the Eklund Mobility Factor is approximately the ratio (in percent) of the optimum NUGP to the actual. A mobility index of less than 100 percent represents an overloaded tire. R. C. Kerr has stated (1954) that, for powered wheels, values of the mobility factor "are reasonably close to comparative actual tractive

coefficients in dry sand In mud the actual tractive coefficient appears to increase at a higher rate I have found cases in mud where $MF^{1.5}$ appears quite reasonable as a basis for correlating tractive coefficient."

To put the Island Mobility Factor into a form comparable with the indices developed in following paragraphs, the inverse of the factor (as a ratio, rather than in percent) may be used, at the expense of some of the system details, giving

$$M_e' = MUGP\left(\frac{2.2}{100.0}\right) \quad (III-1.5)$$

The value of this revised mobility factor (M_e') now decreases with improved performance potential, as do all of the indices following.

2. The WES 50-Pass Trafficability Criterion

In summarizing their 50-pass trafficability prediction work in fine-grained soils, WES in 1956 published two similar regression equations -- one for wheeled vehicles and one for tracked vehicles -- for calculating a "mobility index" from which, using the curve reproduced here as Figure III-1, the soil strength required by a given vehicle to permit it to make 50 passes in the same ruts could be estimated. The soil strength used was the "rating cone index" (RCI) determined by the cone penetrometer and associated procedures [T3 ENG 57, 1959]. The minimum value of rating cone index required by a vehicle was termed the "vehicle cone index" (VCI). The mobility index equation for wheeled vehicles, which will be used here, has since been modified in minor ways a number of times. The latest published version [VMEA, 1965] may be

written:

$$HI = \left[\frac{\frac{NUGP_{average} \times C_v}{\frac{W_1}{1000} \times C_g} \cdot \frac{W_1}{1000} \left(\frac{n_t}{n_v} \right) - \frac{GC}{10} \right] \times f_o \times f_t \quad (III-2.1)$$

where $NUGP_{average}$ = the average NUGP considering the gross weight to be divided evenly among all tires (psi)

n_t = number of tires

n_v = number of wheels (single or dual)

GC = ground clearance (in)

and

C_v = a weight factor

= 0.5 if $GVW < 2000$ pounds

= 0.8 if $2000 < GVW < 4999$

= 1.0 if $5000 < GVW < 9999$

= 1.2 if $10,000 < GVW < 19,999$

= 1.6 if $20,000 < GVW < 34,999$

= 2.0 if $35,000 < GVW < 49,999$

C_g = 1.05 if chains are fitted, 1.00 otherwise

f_o = 1.05 if HP/T < 10, 1.00 otherwise

f_t = 1.05 if mechanical transmission, 1.00 if hydraulic.

Evaluating this equation, and translating t to VCI values via Figure III-1, for a wide range of standard and experimental vehicles show that for practical vehicle configurations

$$VCI \approx 4 NUGP + 14 \quad (t \approx 5) \quad (III-2.2)$$

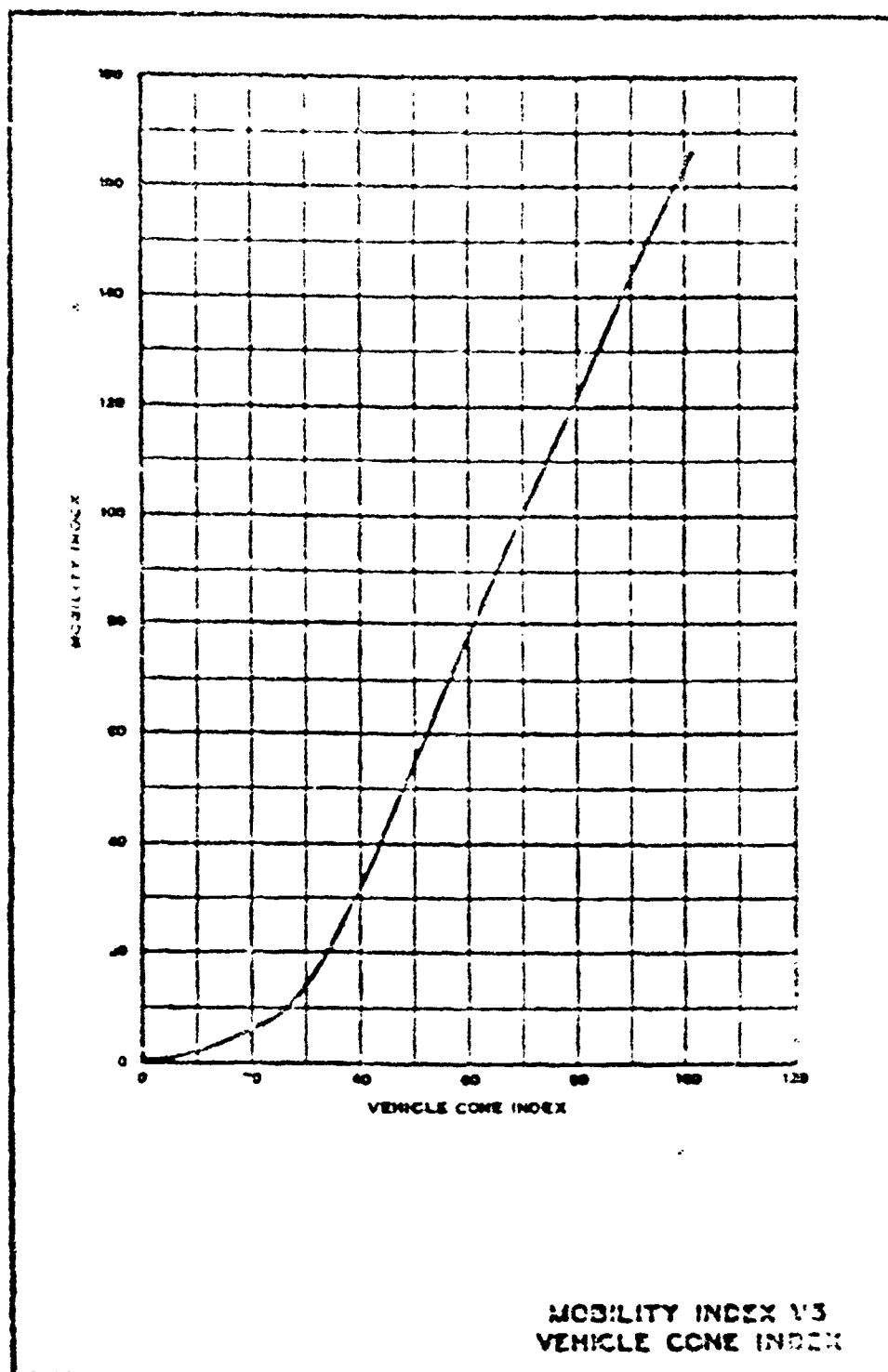


Fig. III-1

3. The $\frac{1}{s_1}$ and $\frac{W_1}{G L_0}$ Tests

In 1962, Freitag and Inight summarized an important group of WIS slope tests of wheeled vehicles in field sand conditions in composite curves which showed that the slope performance of six standard military vehicles collapsed satisfactorily when plotted on the numeric $\frac{1}{s_1}$, where

$$\frac{1}{s_1} = \frac{W_1}{G L_0} \quad (\text{III-3.1})$$

and

- G = the average gradient or slope of the curve of cone penetration resistance (cone index) versus depth of penetration in the top six inches of sand (psi/in)
- L_0 = the average length of the static tire contact patch at operating load and inflation on a hard surface (in).

The field work was done with tires of conventional form so that no conclusions could be drawn as to the effects of tire proportions (b/d).

A more recent consolidation of WIS laboratory data from single tire tests in dry sand [Freitag, 1965] successfully demonstrates a second form of basic numeric for sand:

$$\frac{1}{s_1} = \frac{W_1}{G b^{1.5} d^{1.5}} = \text{MUGP} \left(\frac{1}{2.2 b^{0.5} d^{0.5}} \right) \quad (\text{III-3.2})$$

where Δ = the ratio of radial tire deflection at operating load and inflation on a hard surface (Δ) to tire section height.

To compare the two, note that

$$L_0 = 0.8 \times 2\sqrt{\Delta} = 1.6\sqrt{\Delta} \quad (\text{III-3.3})$$

where Δ = radial tire deflection measured as before (in)

- = $\Delta \cdot h$
- h = tire section height (in)
- = $K_p b$ for a given series of tires,

$$\text{or } L_0^2 = 4K_p^{1.321.321.321.3} \quad (\text{III-3.4})$$

Also, for the tires tested in the field, $K_p = 0.35$.

Substituting (III-3.4) in (III-3.1) and comparing with (III-3.2)

$$\frac{1}{v_1} = \frac{1}{v_0} \left(\frac{0.35}{0.35} \right) \quad (\text{III-3.5})$$

In order to obtain a simple performance index from either of these numerics, consider the point at which slope climbing ability or drawbar pull vanishes. Consider also that all tires are so inflated as to produce a deflection $\delta = 0.25$, which is a practical maximum for reliable slow-speed operation. From the published data, the critical values of the loading numerics are

$$v_1 = 6 \quad (\text{complete vehicles in the field}) \quad (\text{III-3.6})$$

$$v_0 = 4 \quad (\text{single tires in the laboratory}) \quad (\text{III-3.7})$$

Substituting and solving for the corresponding critical sand strength gradients G_1 and G_0 .

$$G_1 = \text{MUGP} \left(\frac{5}{0.350.3} \right) \quad (\text{III-3.8})$$

$$G_0 = \text{MUGP} \left(\frac{8}{0.350.3} \right) \quad (\text{III-3.9})$$

Freitag has observed that the field tests were generally run in damp sands having some slight cohesive strength, while the laboratory tests were in dry sand. It should be noted further that the field tests involved complete vehicles with two or three tires tracking one another. In damp sands especially the following tires in a rut can be expected to develop higher net thrusts than does the lead tire.

4. Preliminary VES Clay Test Results

In his 1965 summary of VES tire test results, referred to in the preceding paragraphs, Freitag also offered a preliminary consolidation of the results of extensive laboratory tests in a remolded fat clay at several strengths on a wide range of tire sizes and shapes. Although all questions were not answered, his preliminary analyses showed that the several facets of single tire performance collapsed well on the basis of a load numeric v_c , where

$$\frac{1}{v_c} = \frac{M_1}{CI_{bd}^{0.5}} = \frac{NUGP}{4} \left(\frac{1}{CI_{A}^{0.5}} \right) \quad (III-4.1)$$

The value of v_c at which drawbar pull vanished appeared to be about 2.5 from which, taking A once more as 9.25, the critical value of CI may be solved for and used as a simple performance index:

$$CI_{crit} = 2.5 NUGP \quad (III-4.2)$$

5. Preliminary First-Pass Trafficability Criterion

During 1963-1964 an independent program was conducted with a number of vehicles in field soils in order to extend the VES 50-pass trafficability contact prediction methods in fine-grained soils to the prediction of first-pass go or no-go trafficability in the same soils (WRE, 1965). The conclusions of this preliminary work were that the average rating cone index required to just permit a single, straight, unaccelerated pass on level soil (= VCI_1 , by definition) was given for wheeled vehicles by

$$VCI_1 = 3 NUGP + 3 \quad (III-5.1)$$

6. The Rolling Resistance of Rigid Wheels in Clay

Correlations and analyses of laboratory tests by the British FRTS on wheels in clay soils have been reported by Uffelman [1961]. For rectangular section rigid wheels, sinkage (z) was found to follow the expression proposed earlier by Brooker [1955] in a brief analytical study of the problem in the light of basic plasticity theory:

$$z = \frac{W_1^2}{q^2 b^2 d} \quad (\text{III-6.1})$$

where q = a uniform pressure over the arc of contact with the soil, identified with the surface strip load bearing capacity of the soil (psi).

Letting $q_1 = \frac{W_1}{bd} = \frac{W_1}{A}$ (III-6.2)

This may usefully be written

$$\frac{z}{d} = \left(\frac{q_1}{q} \right)^2 \quad (\text{III-6.3})$$

Measured rolling resistance (R) was found to correlate well at low speeds and up to sinkages of $z/d \approx 0.1$ with the corresponding analytical expression derived on the assumption that the resistance is due entirely to work of compression on the soil:

$$R = q_1 b = c b d \left(\frac{q_1}{q} \right)^2 \quad (\text{III-6.4})$$

Finally, traction, including side wall traction, was found to agree reasonably with calculations from the simple analytical model:

$$T = c \sqrt{zd} (b + 2z)$$

$$\text{or } T \approx cd \left(\frac{q_1}{q} \right)^2 \left[1 + 12 \left(\frac{q_1}{q} \right)^2 \right] \quad (\text{III-6.5})$$

where c = soil cohesion (psi).

$$\text{Letting } q = N_c + c \quad (\text{III-6.6})$$

where N_c is the bearing capacity constant for a rough strip footing, assumed to vary from 5.7 at the surface to 7.5 at deep sinkage ($z/b > 2.56$), and equating T and R , critical values of cohesion for which resistance exceeds traction are given by

$$\text{NUGP} \left[\frac{N_c + \sqrt{N_c^2 - 8(d/b)}}{4N_c} \right] \leq c_{\text{crit},T} \leq \text{NUGP} \left[\frac{N_c + \sqrt{N_c^2 - 8(d/b)}}{4N_c} \right] \quad (\text{III-6.7})$$

The lower limit is of no practical interest in the present context because, in such weak soils, even though traction is theoretically available sinkage will be excessive. The equations indicate that side wall traction will effectively prevent traction failure in relatively narrow wheels

$$\frac{b}{d} \leq \frac{8}{N_c^2} \quad (0.25-0.14, \text{ depending on } N_c) \quad (\text{III-6.8})$$

regardless of loading.* In this case, a sinkage criterion must control. If, to be consistent with the constraints of the analysis, $z/d = 1/9$ be taken arbitrarily as the upper limit of allowable sinkage, then

$$c_{\text{crit},z} = \text{NUGP} \left(\frac{1.5}{N_c} \right) \quad (\text{III-6.9})$$

*This may merely be a result of simplifications made in the analysis to facilitate simple mathematical treatment.

The traction criterion will govern for tires having b/d ratios above 0.25 to 0.33 (depending on N_q); i.e., for all normal tire sizes in current use. Note that without side wall traction

$$T = c \cos \left(\frac{\pi}{4} \right) \quad (\text{III-5.12})$$

In this case, traction failure is always possible, and will control. The critical value of soil cohesion is approximately one-half the above values:

$$c_{\text{crit},T} = 0.5 \text{ NUGP} \quad (\text{III-6.11})$$

For use as indices, and with some loss in theoretical power, equations (III-6.7) and (III-6.9) may be evaluated for an arbitrary value of $N_q = 5.7$:

$$c_{\text{crit},T} = \text{NUGP} \frac{1 + \sqrt{1 - 0.25(b/d)}}{4} \quad (\text{III-6.12})$$

or, for $b/d < 0.25$,

$$c_{\text{crit},T} = 0.254 \text{ NUGP} \quad (\text{III-6.13})$$

7. The LLL Soil Value System and Vehicle Model

Use of the LLL soil value system and vehicle model as a potential design tool has been demonstrated a number of times [Harrison et al., 1953, 1959; VMEA, 1965; etc.]. The LLL soil value system measures two sets of soil parameters, one related to sinkage (K , n , etc.) and the other to direct shear reactions (c , ϕ , etc.), using a series of plate penetration tests and a normally loaded annular shear vane, respectively. The two sets of parameters are treated as independent. The soil-vehicle model has been developed in several degrees of complexity to incorporate allowances for a number of detailed

types of behavior. These refinements are largely unverified experimentally, however, and it is adequate for present purposes to utilize the unelaborated model. For tires in clay and silt soils, this gives

$$z = \left[WUGP \left(\frac{d^{0.5}}{A} \right) \left(\frac{1.5}{3-n} \right) \right]^{\frac{2}{2n+1}} \quad (\text{III-7.1})$$

The motion resistance arising from soil compaction (i.e., neglecting "bulldozing resistance") is

$$R = \frac{bK}{n+1} \cdot z^{n+1} \quad (\text{III-7.2})$$

Traction, assuming adequate tread to develop soil-to-soil shear failure, is assumed to be given by

$$T = cb \sqrt{3z} + W_1 \tan \phi \quad (\text{III-7.3})$$

where $\tan \phi$ = apparent angle of internal friction of the soil.

The soil properties at which $R = T$ may, as before, be used as indices of limiting soft-soil performance. By fixing values for n and ϕ to represent classes of soils, it is possible to reduce the problem to that of finding a critical minimum value of the soil consistency parameter "K." Because of the several independent variables involved, it is convenient to develop expressions for " K_{crit} " for specific soils. Consider for example a sandy loam: $n = 0.3$, $c = 0.56$, $\tan \phi = 0.31$. The assignment of "n" gives

$$z = \frac{0.6 d^{0.5} WUGP}{K} \quad (\text{III-7.4})$$

Thus, on a sinkage basis, arbitrarily taking $z/d = 0.3$ as the practical sinkage limit:

$$K_{crit,s} = WUGP \left(\frac{2}{d^{0.5}} \right) \quad (\text{III-7.5})$$

Also,

$$\frac{R}{W} = \frac{0.62 \text{ NUGP}^{0.5}}{2^{0.43} K^{0.5}} \quad (\text{III-7.5})$$

For the assumed sandy loam

$$\frac{T}{W} = 0.31 \left[\frac{2/T}{\text{NUGP}^{0.5} K^{0.5} 2^{0.43}} + 1 \right] \quad (\text{III-7.7})$$

The last two equations together give

$$K_{\text{crit},T} = \frac{4}{\sqrt{3}} \text{NUGP} \left(1 - \frac{\sqrt{2}}{\text{NUGP}} \right)^2 \quad (\text{III-7.8})$$

The sinkage criterion will govern for all cases except when $\text{NUGP} < 4.85$ psi.

For clay soils, assume $n = 0.5$ and $\tan \phi = 0$.

Then z and R are as before (eq. III-7.4 and III-7.5) and

$$\frac{T}{W} = \frac{1.55 c}{\text{NUGP}^{0.5} K^{0.5} 2^{0.43}} \quad (\text{III-7.9})$$

Equating R/W (III-7.6) and T/W (III-7.9), the soil consistency K drops out and the minimum value of cohesion may be solved for

$$c_{\text{crit},T} = 0.4 \text{ NUGP} \quad (\text{III-7.10})$$

The sinkage criterion is the same as for the sandy loam (III-7.5). In order to determine where each criterion governs, assume that at sinkage $s/b = 2.35$, $p = 7.5 c$. Then, from the basic defining LLL system equation $p = Kz^n$, remembering that n has been taken as 0.5,

$$K = \frac{4.7 c}{b^{0.5}} \quad (\text{III-7.11})$$

This, taken with (III-7.10) and III-7.5) indicates that the traction criterion (III-7.10) will control for tires where $b/d < 0.88$.

When the procedure is repeated for a uniform, fat clay in which $\alpha = 0$, the analysis becomes identical to the VRE analysis, without side wall traction, and the critical value of cohesion is

$$c_{crit,T} = 0.500 \text{ NUGP} \quad (\text{III-7.12})$$

which governs in all cases.

8. An Aside

In section 2 of this appendix, the WES equation for calculating the 50-pass trafficability requirements of wheeled vehicles in fine-grained soils was simplified, at the expense of some precision, to

$$VCI_v \approx 4 \text{ NUGP} + 14 \quad (\text{III-2.2})$$

Similar mistreatment of the corresponding equation for tracked vehicles [see VMEA, 1965] leads to the following approximate equation for a range of existing tracked vehicles:

$$VCI_t \approx 4 \text{ NUGP} + 16 \quad (\text{III-8.1})$$

The preliminary equation for the vehicle cone index of wheeled vehicles required to permit a single pass is given in section 5 as

$$VCI_{1,v} = 3 \text{ NUGP} + 3 \quad (\text{III-5.1})$$

The corresponding preliminary equation for tracked vehicles from the same source [WRE, 1965] is

$$VCI_{1,t} = 3 \text{ NUGP} + 6 \quad (\text{III-8.2})$$

Consider now a tracked and a wheeled vehicle having equal 50-pass trafficability requirements (VCI) according to equations III-2.2 and III-8.1:

then $k \text{ MUCP} = 14 = k \text{ MUCP}_t = 15$

or $\text{MUCP}_t = \text{MUCP}_s = 0.5$ (III-8.3)

Similarly, for equal one pass requirements (VCI_1),
from equations III-5.1 and III-8.2:

$\text{MUCP}_t = \text{MUCP}_s = 1$ (III-8.4)

Thus it appears that for the same basic soft-ground
crossing ability, the nominal unit ground pressure
of a vehicle on tires (as defined in eq. III-8.1)
may be 0.5 to 1 psi greater than that of a comparable
tracked vehicle, as normally defined.

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<p>10. DOCUMENT ABSTRACT</p> <p>The state-of-the-art of off-road vehicle design, especially of military vehicles, is surveyed with particular reference to those design elements which especially distinguish off-road vehicles from related equipment. The procedures by which off-road military vehicles advance from concept and/or requirement to field issue are also reviewed, and some relations between apparent technical weaknesses and the administrative procedures are pointed out. It is concluded that to provide the more active vehicles needed by the Army in the field in Southeast Asia a complete second family of off-road military vehicles is required--an integrated, compatible system of vehicles optimized for operations in Southeast Asia rather than in Europe, as is our present standard fleet. Organizational changes which would speed such an approach are suggested.</p>	

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